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ICBM OVERTEST TECHNOLOGY

FINAL REPORT

VOL II

HERCULES INCORPORATED
SYSTEMS GROUP
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FOREWORD

This report was submitted by Hercules Incorporated, Bacchus Works, Magna, Utah 84044 under Contract F04611-73-C-0010, Job Order No. 305910LY with the Air Force Rocket Propulsion Laboratory, Edwards, CA 93523.

This report has been reviewed by the Information Office/DOZ and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

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This is the final report on the ICBM Overtest Technology Program which was Performed by Hercules Incorporated for the Air Force. The primary objective of the program was to develop overtest technology for the prediction of ICBM motor service life. An important secondary objective was to make predictions of the M57A1 motor life. The most critical failure modes were shown by analysis and verified by analog subscale and full-scale motor tests to be wing slot cracking and aft centerport debonding in

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SECTION VI

OVERTEST METHODOLOGY FOR PREDICTION OF ICBM SOLID ROCKET MOTOR SERVICE LIFE

A. INTRODUCTION

Overtest technology may be applied to ICBM motor service life programs for the following principal purposes:

(1) Verification and/or identification of the most critical failure modes

(2) Experimental determination of motor structural integrity after selected periods of aging

(3) Verification of mathematical predictions of aging effects and motor service life

Overtest in the context of this report applied to the testing of solid propellant rocket motors or motor components by the application of the same types of loads and/or environments that occur in normal operation but to levels more severe than normal. Although the concept is generally applicable to all motor components, the methodology defined herein is primarily limited to the propellant grain failure or related failure modes. Overtests may be performed on full-scale motors or on analog devices appropriately designed to represent the stress and strain conditions associated with a particular failure mode. In either case, the overtest must be capable of identifying the conditions of failure and a means for relating this information to reserve strength of the motor must be available.

Overtesting should be considered as complementary to other techniques essential to a meaningful service life program. Major elements of a comprehensive predictive aging surveillance and service life program encompass laboratory characterization, including accelerated aging, and mathematical analysis, in addition to full-scale and subscale overtests. Motor dissection and associated materials characterizations are considered as an inherent part of overtest technology.

The use of overtest technology in aging and surveillance programs depends upon the time in the life of the motor system that the concept is introducted. The program on which the technology given herein is based was planned around the Minuteman II, stage III motor that has been deployed since 1965 and is no longer in production. Therefore, the results are directly applicable to the first type of motor system of interest, namely, motors that are in an operational force no longer in production. The second type of program of interest is directed at motors that are in development, qualification, or early production.

The ICBM overtest program reported in Volume I, Sections I through V was used as the principal basis of the overtest technology plan presented in this section. Not all of the essential elements of a general overtest plan for use in predicting ICBM motor service life are supported by the overtest program results. However, for completeness, other elements recognized as necessary based on experience and other program results are presented such that this section of the ICBM overtest final report can be used as a guide for application of overtest technology.

In the following presentation, the desired (and perhaps somewhat idealistic) approach to overtest is presented. It is recognized that particular problems may arise which make it impractical or impossible to follow the prescribed approach. Therefore, specific problems are considered and alternate approaches are recommended. The general approach is given first. This is followed by a presentation and explanation of the main elements of an overtest program. Overtest procedures plus those elements necessary for interpretation of the overtest results collectively provide the essential ingredients of a meaningful predictive surveillance program for ICBM motors.

B. GENERAL APPROACH

The general approach for application of overtest technology is diagrammed in Figure 6-1. The program divides logically into three principal phases which are:

Phase I - Definition

Phase II - Overtest and Inspection

Phase III - Interpretation

The definition phase encompasses a review and definition of failure modes and the selection of applicable overtests. Phase II is directed to the actual performance of the overtests and the posttest examinations and materials characterizations. The final phase is the interpretation of overtest results in association with results from mathematical analyses and other surveillance and aging tests. The approach depends upon the system being evaluated. Motors that are already in service and are no longer being produced requires one type of planning, whereas those still in production require another.

In planning an overtest program for the motors no longer being produced, it is necessary to consider motors that are being removed from the force, usually for reasons other than for surveillance testing. Consequently, there is limited flexibility in planning a program because selection of a particular age or class of motor and propellant lot is usually prohibited. Moreover, the history of a particular motor removed

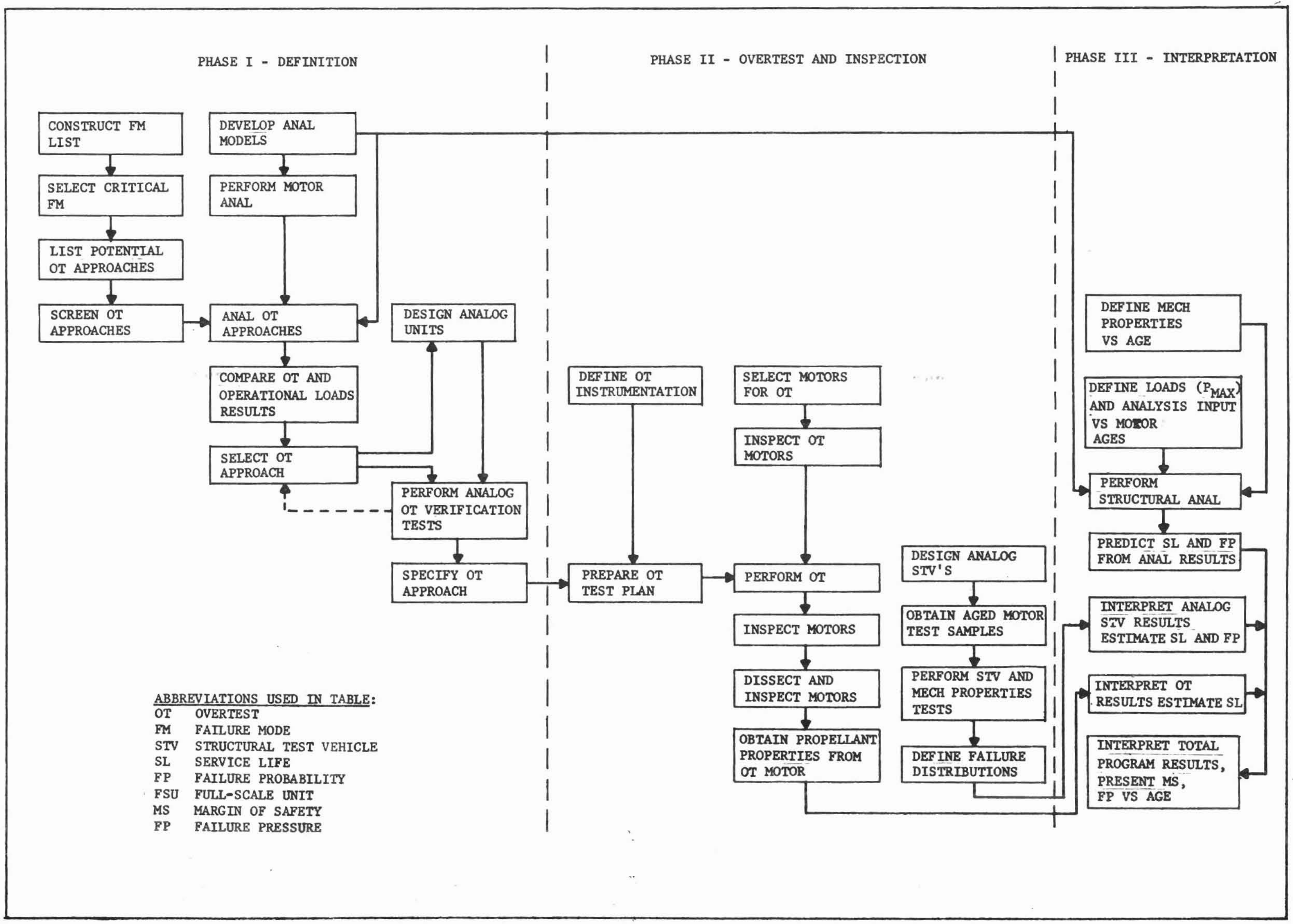

Figure 6-1. ICBM Overtest Technology Program

from the force may not be sufficiently well known to permit confident controlled experimentation. Usually, the specific propellant properties of a particular overtest motor taken from the force will not be known beforehand and propellant for fabrication of analog test devices will not be available. For some types of loading, the potential for additional useful instrumentation exists for motors still being manufactured, but motors already completed have limited instrumentation possibilities.

The initial task in planning the overtest program is to define the failure modes that are to be investigated. This is usually accomplished by identifying the potential modes and screening the list to arrive at those considered as critical. Once the critical modes have been determined it is then necessary to choose overtest approaches that are applicable to each of these modes. Analyses of the motor and candidate overtest vehicles are performed to confirm the overtest approach and the test procedures. The overtest approach should be demonstrated and failure modes verified prior to commiting to a long-range test program such as aging and surveillance. The ideal overtest program should involve a combination of full-scale and analog test vehicles.

A detailed log of overtest motor (or analog device) history should be maintained. It is desirable to know properties, geometry, previous loading, and other similar characteristic data for a particular vehicle so that results may be interpreted relative to a total motor population. This desire leads to detailed before and after inspections and properties tests from dissected motors following the test. Plans should encompass subscale tests to predict variability of failure loads and define failure distributions.

Interpretation of the overtest results involves results from a small number of full-scale overtests and a larger number of subscale or partial motor analog overtests. Each of these tests are designed and instrumented to provide quantitative values which can be directly related to structural integrity relative to a particular failure mode. Theoretical analysis are also performed using properties for the propellants used in test vehicles. Extrapolation of results to other motors and time periods is based on correlations between analytical and experimental results and the necessary mechanical properties for theoretical analysis of the population not represented by the overtest.

The goal of the general overtest/predictive surveillance program is to provide reliable predictions of the motor service life. In doing so, the objective is to involve the latest experimental and analytical methodology in a complementary analytical and experimental program.

The major elements of the overtest program approach are presented in the following paragraphs. The plan is first presented according to the three principal phases identified above. This is followed by a more

comprehensive coverage of specific segments which are considered to be the key to the success of the program. These key program elements are: (1) Propellant characterization, (2) analysis, (3) instrumentation, (4) analog tests, and (5) full-scale tests.

C. PHASE I - DEFINITION

The following tasks should be accomplished during Phase I:

(1) Selection and Screening of Failure Modes

(2) Overtest Program Definition

  (a) Overtest Approach

  (b) Test Vehicles

(3) Program Plan

1. Definition of Critical Failure Modes

The initial objective of an overtest program is to determine the critical failure modes. This objective is extended for purposes of service life predictions to define those modes which are most likely to limit the operational life of the motor in question. This is accomplished by mathematical analysis and related experience. For a motor that has completed development, the potential modes may be identified by associating them with development problems. Problems encountered during the development and operational life of similar motors may also suggest potential failure modes. Structural analyses should be performed first using unaged materials properties. The latest state-of-the art for structural analysis should be applied with a complete characterization of materials properties. This analysis should provide margins of safety for all critical failure modes such that a relative ranking of failure modes can be accomplished by comparison of margins of safety. A definition of the critical loading environments and mission requirements should be determined in the development program and applied in the basic system analysis.

In defining critical age-related failure modes, anticipated aging of materials and the effects on the margins of safety must be considered. Aging of materials could possibly reduce a comparatively large margin of safety to an unacceptable value during the desired lifetime of the motor. Thus, a particular mode could become more critical than one exhibiting a smaller margin of safety in the unaged condition but which is not affected by aging. The result is a change in ranking of failure mode criticality with age. Structural analyses should be repeated in the

same manner as in the baseline analysis but with properties accounting for aging effects. This necessitates some type of accelerated aging program to complement the overtest program. The general predictive surveillance program should be planned to provide properties at selected aging times sufficient to allow a complete analysis at each aging time chosen. The selection of key aging parameters and the approach for conducting an accelerated aging program to support analyses to predict aging effects on failure modes is beyond the scope of this report.

To establish which failure modes are most likely to become critical, the following basis guidelines should be recognized in screening failure modes for the overtest program:

(a) Low margins of safety obtained by analysis indicates that only small degradation due to age can take place without causing a problem. Therefore, failure modes for which margins of safety are low or are predicted by analysis to fall below acceptable levels during aging should be treated as critical.

(b) If materials suspected of being sensitive to aging are involved, an aging problem should be considered although the predicted margins of safety are relatively high.

(c) Problems known to have occurred in the motor previously or in similar motors should be considered critical until it can be satisfactorily proven that the problems will not arise in the subject motor as a result of age.

The information necessary to evaluate failure modes by the above criteria should be organized in tabular form according to Table 6-1.

Normally, there are only one or two critical failure modes in a typical ICBM motor and by the end of a development program they are usually known. This is not to say, however, that the overtest program for service life prediction should be so limited. A discussion of grain and case-bond failure modes is given in Reference 1. In order to limit the overtest program to an economically feasible scope, particularly if full-scale overtests versus age are to be performed, it will be necessary to screen the failure mode list and reduce it to only the most critical ones for further study.

2. <u>Choosing the Overtest Approach</u>

The objective of this segment of the overtest program is to screen the potential overtest methods and to define appropriate tests for determining motor integrity with respect to failure modes identified as being critical.

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[1] References are presented at the end of this section

TABLE 6-1

FAILURE MODE EVALUATION[1]

Typical Modes of Failure	Critical Physical Properties	Load or Environment
Grain cracking or unbonding	Propellant long-term stress or strain; relaxation modulus, case-bond strength at temperature extremes	Temperature cycling
Debonding due to degradation of case-grain bond strength and case expansion	Short time strength of case bond at elevated temperature	Aerodynamic heating
Slump, debonding, checking of flow	Case-bond shear strength, propellant relaxation modulus	Axial acceleration
Slump, case ovality	Case stiffness properties, propellant modulus	Transverse acceleration
Autoignition, propellant degradation, fatigue fracture	Propellant ballistic properties, notch sensitivity, fatigue properties	Vibration
Debonding, case bending	Case and case-bond stiffness and strength, propellant modulus	Shock
Case bending, debonding	Propellant and case-bond fatigue properties	Transportation and handling
Grain cracking, debonding	Endurance tensile strength of propellant, biaxial tension, case-bond tensile strength	Cure shrinkage
Grain cracking, debonding	Failure strain from pressurized biaxial tension at appropriate rates	Pressurization

[1] See List of References at end of this section

There are several overtests which may be devised to study grain structural integrity. Often a test which involves one particular type of loading may be used effectively to represent another load. All potential overtest approaches should be considered. Some such candidate approaches are presented in following paragraphs. Analytical models should be devised for analysis of the most promising overtest approaches and actual motor operation. Selection of the overtest approach will depend upon the representation of actual critical motor conditions by the overtest.

Structural analysis methods are available by which motors may be analyzed for operational loads and overtest and for meaningful comparisons of the two. Overtest parameters which can be monitored during test can be analytically predicted for use in the test planning. The analyses should emphasize all potential failure modes of the grain and case bond and the possibility of the order of criticality of modes changing with age.

Since the full-scale motor test is generally planned around a specific failure mode, some assurance is required to demonstrate that failure can be made to occur as predicted. This may be accomplished by tests-to-failure of subscale or analog specimens representative of the full-scale unit and the motor failure conditions. The subscale structural tests must be related to full-scale overtests and actual motor structural performance by state-of-the-art analysis techniques. Instrumentation techniques and failure detection should be demonstrated in the subscale verification tests if possible. This phase of the overtest technology program may be considered as verification that the analysis can predict and identify conditions of failure in the motor.

Although various types of overtests have been applied in past programs, not all are particularly applicable to ICBM programs. The overtest approach is geared to the critical loading conditions which should be identified as a part of the failure modes definition task. The overtest loading program for full-scale (and analog) units must represent realistic loads. Loads which are critical to one type of solid propellant motor are not necessarily critical to another.

The principal loads of interest for ICBM motor overtest consideration are:

(a) Transverse and axial accelerations

(b) Vibration

(c) Differential cure and/or thermal shrinkage

(d) Internal pressure

Those loads known to be of concern in ICBM motors which contain CMDB propellants such as the M57A1 are primarily due to internal pressure. Some motors must withstand significant residual thermal and cure shrinkage stresses; however, once they are deployed in the field, the combination of long-term storage under strain followed by pressure becomes the primary concern. Acceleration has been of major significance in a number of Hercules flexible-case motor designs (Sprint and HIBEX) but present ICBM accelerations are relatively low and have not been shown as critical in past ICBM motor failure studies. Vibration, particularly during transportation and handling, has received much attention but has not apparently been a problem with ICBM motors. Acoustic vibrations are of significance with regard to attached motor hardware but do not apparently represent any problem to the motor grain structural integrity.

Experience, therefore, has shown that the major concerns for ICBM motors are associated with high rate pressurization and shrinkage loading. From an overtest point of view the pressure tests are more challenging and are emphasized here. Mention is made of the other overtests but detailed consideration is more within the scope of other programs.

a. Acceleration Loading

Acceleration tests normally are performed by mounting a subscale or full-scale motor on the arm of a centrifuge with the axis of the motor postitioned properly with respect to the center of rotation to give the desired acceleration direction. Magnitudes of acceleration forces depend upon the rate of rotation. For a significant test, the length of the centrifuge arm should be large relative to the motor dimensions. This type of test was used as a development test and check on the analysis in the development of the second stage Sprint motor. In the Sprint tests, the accelerations were less than flight accelerations. Longer loading times on the centrifuge were related to flight times by taking into account relaxation of the propellant. Damage resulting from a low level of loading applied over a long duration can be equated to damage due to higher loading applied over a shorter period.

In using partial-motor analog devices, the loads are often applied in the laboratory by conventional type test equipment. In such cases it becomes necessary to duplicate the stress field created by the accelerations. The problem then becomes a problem of analog design around available methods of loading instead of developing a special loading technique.

b. Vibrations

Vibration loading ordinarily represents no particular difficulty; most motors are subjected to vibration testing as a normal part of environmental qualification tests during development and many facilities are equipped to overtest in the vibrational modes. However,

careful attention must be given to possible localized heating and resulting failure of the grain or igniter. Unlike other loads, the effects of vibration loading are dependent upon heat transfer considerations resulting from viscoelastic behavior of the propellant in addition to stress levels. A region with relatively lower stress level compared to another region may be more critical from a point of view of integrity because it may not lose the heat generated by the stresses resulting from vibrations.

c. Shrinkage Loads

There has been much testing of full-scale and analog motors under cure and thermal loadings. No unusual problems are expected in performing this type of test other than those related to instrumentation and relating test results to actual operational loads. Once the temperature limits and rates of cooling are known, the overtest program can be planned around conditioning equipment available at most rocket motor facilities.

One problem to be addressed and forwhich a direct overtest approach is not immediately obvious is reduction in reserve strength resulting from long-term storage with the propellant subjected to residual loads created by cooldown during manufacture. Other Air Force programs such as the LRSLA and SLIM programs possibly could be sources for applicable overtest technology in this area. Subscale and partial motor analogs should figure strongly in overtest programs involving long-term storage under loads.

The thermal cooling overtest approach should be considered as a possible means for analysis of pressure loading. It has been shown that a definite analogy can be drawn between thermal and pressure loads.[2] Particular properties of the propellant and the failure mode in question determine whether the thermal test is feasible as a pressure overtest. In some situations the propellant strength capabilities may possibly increase with reduced temperature at a rate relative to the load that makes it impractical to achieve failure at reasonable temperatures.

d. Pressure Loading

Pressure testing is not as straightforward as others cited. Not only must the pressurization rates and levels be represented, but safety is a prime consideration. The success of a test to simulate the ignition transient which is usually the critical period depends upon how well this load condition is duplicated. The period between time zero and achievement of firing pressure is of principal concern. Since propellant response is highly dependent upon loading rate, a low-rate pressurization test (which would eliminate many of the problems associated with this type of testing) is not sufficient. On the other hand, improperly designed tests and equipment have resulted in dynamic overshoot and short-term pressure spikes much in excess of the desired maximum pressure, inadvertent ignition of the grains, and nonrepresentative grain cracking because of too-rapid loading. Gas pressurization, such as with nitrogen, should be

avoided if possible because of compressibility of the gas and resulting loss of control of loading and the inherent safety problem, if a motor case should fail during testing.

Hercules has resolved most of the problems with high-rate pressurization tests and has developed special techniques and equipment for this purpose. Tests have been performed up to 50,000 psi/sec. Minuteman II, stage III (M57A1) pressurization rates have been duplicated very closely, and motors have been tested to pressure levels in excess of failure. It is important that pressurization rates be confirmed in checkout tests prior to overpressure tests to ensure close agreement between test rates and pressures and those of the motor during operation.

An important result of the ICBM overtest technology program is the demonstration of the cold pressurization test as a viable overtest for ignition rate loading. Further confirmation for the approach has been obtained from the LRSLA program and, in subscale devices, from the Trident C-4 program.

e. Miscellaneous Loads

Other overtest methods should be considered and evaluated based on the requirements of a particular program. Analog devices loaded by conventional laboratory equipment and designed to duplicate stress fields due to pressure are essential to a good statistical approach. The representation of pressure loads by thermal testing was mentioned in the discussion of thermal overtests.

Other overtest possibilities include motor firings wherein an oversized igniter is used or the nozzle throat is reduced to raise the pressurization rate and/or the firing pressure to achieve an overtest. Higher pressures may also be achieved by modification of the grain surface in a noncritical area of the grain. Firing at a temperature that causes higher than normal stresses is also an overtest possibility. All of these tests wherein a hot firing is used have the disadvantage that exact failure levels are not identified since the tests are not normally designed to obtain failure. Rather, the grain integrity is demonstrated at a preselected level of overtest dependent upon the load. The advantage is that the test is ordinarily considered more realistic.

Emphasis has been placed on overtests of motors in "as-built" condition, i.e., at zero burn. Failure modes that become critical at intermediate burn times could possibly be evaluated in a firing wherein motor firing utilizing small nozzles is terminated by cutting off the dome and quenching the propellant at a preselected time. Success in performing this type of overtest depends upon selecting a time to extinguish such that grain failure would have begun but not progressed to the point of total failure of the motor. Hercules has been successful in performing this type of test with subscale and full-scale units.

3. Selection of the Test Vehicle

The basic test vehicle or vehicles for an ICBM overtest program should be chosen on the basis of the following considerations:

(a) Objective - Is the overtest to confirm failure modes, demonstrate adequacy of analytical technique, or provide failure levels and structural capability directly? Will the tests be performed throughout a long-duration aging and surveillance program? Is the test to be the principal source of aging data or does it serve to complement other methods? Can results be correlated with other phases of the program.

(b) Safety - Will the methods of overtest or instrumentation create a hazard for life or property? Will extraordinary (and expensive) precuations be necessary to guard against such possibilities?

(c) Motor and Loads Simulation - How much flexibility is afforded in varying loads? Are the critical conditions truly simulated? Can representative storage conditions be applied prior to the test? Will failure occur in what is postulated to be the critical mode? How certain is the simulation?

(d) Instrumentation - Can the device be instrumented to detect failure loads and determine initial failure location? Will instrumentation affect critical stress fields?

(e) Statistics - Can the devices be stored and tested economically in sufficient numbers to provide statistical significance? Can it be made to represent various populations and/or motors as necessary?

(f) Manufacturing - Can it be manufactured by representative processes, or, if for an operational motor, can it be manufactured from an actual motor?

(g) Interpretation - This consideration involves most of the above. The primary concern is to assure that the method of interpretation is not misleading. Is it capable of reliable analysis?

Following the selection of a particular device for use in the overtest program, it should be justified for use in a comprehensive aging and surveillance program to the greatest extent possible by analysis and experiments.

Two basis types of test devices may be considered for use in an ICBM overtest program. These are: (a) Full-scale motors, and (b) motor analogs. Each of these devices is discussed briefly in the following subparagraphs.

a. Full-Scale Motors

Tests to study motor structural capabilities with regard to the critical failure modes must be representative of the actual motor, its loads, and its environments. The least questionable approach, assuming it is successfully carried out, is the full-scale motor overtest. However, the expense associated with full-scale ICBM motor overtests can be great due to handling, instrumentation, and test setup, even when surplus motors are available. Therefore, the full-scale test is not expected to be an optimum approach for obtaining data in sufficient quantities for statistical interpretation. The principal uses of the full-scale motor overtest are to: (1) Demonstrate or verify more applicable and economical approaches, (2) verify the critical failure mode selection, and (3) identify failure modes other than those postulated as the critical ones.

There are generally fewer questions in relating full-scale motor overtest data to actual applications. Fewer analogies with the real operational conditions are required assuming loads are adequately duplicated by the test. Also, the full-scale motor offers more flexibility in load simulation in that some overtests can be developed around existing handling, storage, and firing procedures. The full-scale motor can be used in all load simulations previously discussed plus it can be modified slightly and fired to achieve an overtest.

The use of full-scale motors in a pressure overtest program is described in Paragraph J of this section.

b. Analog Tests

Basically, there are two choices in selecting analog test devices. One is partial simulation by partial-motor-analog tests. Several partial-motor analogs in combination provide confirmation of the theoretical analysis or, alternatively, an experimental analysis of the motor. The second is subscale motor analogs in which all critical regions and loads of the full-scale motor may be simulated. Generally, practical limitations prevent the use of complete subscale analogies of large motors wherein all significant features with respect to all potential

failure modes are simulated. Development of such an analog is paramount to developing a new motor. Consequently, subscale motor analogs (or analog motors, as they are often called) are really partial-motor analogs. They are usually distinguished from the partial-motor analogs identified above in that they provide a three-dimensional analogy and, therefore, a more realistic representation of one failure mode of a motor. In this report, when reference is made to subscale motor analogs, what is meant is some type of subscale cylindrical device which could be a partial-motor analog emphasizing one or more critical failure modes.

Both basic types of motor analogs are recommended for ICBM surveillance and overtest programs. Both are considered vital to the success of a predictive surveillance program. Partial-motor analogs serve as an economical device which can be tested in large numbers to obtain statistically significant data (descriptive of the entire motor population). Subscale motor analogs provide an intermediate check between the full-scale motor and the partial-motor analogs. The subscale motor analogs to be necessarily limited in number will provide failure data representative of the mean value of failure probability distributions; whereas partial-motor analogs will define the variations about the mean.

The design and application of partial-motor analog devices to an overtest program are presented in Paragraph I of this section.

D. PHASE II - OVERTEST AND INSPECTION

The failure modes, overtest approach, and test vehicle types were defined in Phase I. The objective of Phase II of the overtest program is the design and conduct of the experimental program.

The major elements of Phase II are:

(1) Design of analog devices

(2) Instrumentation plan

(3) Motor selection

(4) Test planning

(5) Pretest and posttest inspection

(6) Overtest

(7) Propellant mechanical characterization

Analog devices are designed to determine grain integrity for the loads, environments, and locations of concern. Analysis methods for the motor and analog should be fundamentally the same. Applicability of the analogy is based on the analysis results. Absolute quantitative values

obtained by testing of the analogs will not necessarily be used directly in a strength analysis; therefore, the major concern should be to define a device that will possess the same type of stress field under load as the real motor. Loading of the analog may not be the same as the motor. For example, a tensile load may be applied to a partial motor analog to generate a stress field which duplicates (according to analysis) the motor stress field in the region of interest. The success of the analog test program depends upon being able to obtain a relationship between analog failure loads and motor failure loads. Failure of the analogs can then be interpreted in terms of structural capability of the motor without the benefit of a precise failure criterion for the propellant.

The analog test approach should be verified for the particular failure mode it is supposed to represent. This should be one of the first steps in Phase II. Verification involves demonstration that the analog can be made to fail as desired, that the failure levels can be confidently measured and a correlation with motor failure loads can be achieved. Since a relationship between motor and analog failure loads is being sought, it therefore becomes necessary to accomplish a full-scale motor test early in the program. If possible, the analog test specimen should be made from propellant removed from a lower-strain (undamaged) region of the full-scale motor which was overtested.

In checking out a partial motor analog, it may be necessary to verify applicability by checking it against a better (but probably larger and more expensive) analog vehicle. This would occur when a full-scale motor is not available, the verification analog is unacceptable for a large-volume program and confidence in the verification analog as a substitute for the full-scale motor has already been established.

Following the development of the basic analog device, a sufficient number of analog tests should be performed for each failure mode to obtain a basis for determining probabilities of failure.

The general approach to Phase II has been presented thus far. In summary, it involves design of the analog, demonstration of the functioning of the device in checkout tests, performance of a full-scale motor (or suitable substitute), overtest to verify the analog and establish corrections for interpretation. Finally, application is made by overtesting the analog devices to obtain sufficient data to statistically evaluate particular failure modes.

It is important to recognize that it usually is not possible to perform enough full-scale motor overtests to obtain a realistic statement of grain structural capability of the entire motor population. The tendency to overemphasize results from a single overtest should be resisted. The key to a successful overtest program is in achieving a good economical analog device. Therefore, the greatest significance of the full-scale overtest is in the verification of the analog.

Individual paragraphs in this report are devoted to the discussion of analog and full-scale overtests (Paragraphs I and J, respectively). Analysis (Paragraph G), instrumentation (Paragraph H), and propellant characterization (Paragraph F), which are essential to the work performed in Phase II, are also presented individually. Test plans and operating procedures are contained in the test sections.

The usefulness of overtest technology depends upon the care with which it is carried out. Therefore, it is essential that motors made available to the program are applicable. They must be representative of the population of motors being evaluated. Therefore, the use of motors that have been rejected for other purposes (which is often the situation) should be evaluated thoroughly to avoid misleading results. Motors should be chosen for an aging and surveillance program from subsets of operational motors based on the time of manufacture. Propellant should be withdrawn from the production program at the same times as full-scale units for use in analog tests and for characterization tests. Generally, it will be desirable to make provisions for analog tests and characterization tests on propellants which are representative of several manufacturing times in addition to those represented by full-scale motors. Obviously, this idealistic plan cannot be applied to motors which are no longer in production.

Motors, propellant, and analog devices from the various manufacturing subsets should be stored and tested in exactly the same way. A program planned in this way will make possible the separation of aging effects and changes resulting from manufacturing differences. It also provides for failure data applicable to individual subsets of motors as well as the entire population of operational motors; alternatively, a program defined in this way can indicate whether the motor population is homogeneous or composed of definable subsets.

For a new motor program the number of analog tests and full-scale tests should be planned to provide statistical significance. The absolute number will depend upon the performance (repeatibility, etc) of the test devices and the particular propellant. The total scope of the overtest program to support a predictive surveillance program should be defined in Phase II immediately following the acceptance of analog devices for the program. It should be completed by no later than the beginning of the production program.

It is essential that each unit of the overtest program be completely characterized. The exact condition of full-scale units must be known prior to test and the effects of the overtest must be adequately documented. Propellants from the exact test units must be characterized by appropriate mechanical properties tests. A sectioning and test plan must be developed based on the structural response of individual motor designs. In planning this phase of the overtest program it should be recognized that the overtest motors must serve as a source for properties to be used in complementary analytical studies to predict service life.

Sectioning and visual inspection is the most, and perhaps the only, reliable means for determining the extent of failure from a motor overtest. Other inspection techniques that are available are presented in the full-scale motor overtest section of this report (Paragraph J).

E. PHASE III - INTERPRETATION

Phase III is the interpretative phase. Not only will it be necessary to interpret each overtest individually and the overtest program totally, but the results must be interpreted along with complementary portions of the predictive surveillance program. The major interfaces will be with full-scale motor firings, environmental tests during development, and theoretical analyses. Motor service life projections should be made with due consideration of all of these potential sources of information.

It is to be assumed that the full-scale overtest to failure of an individual motor is the absolute base against which all other methods of obtaining the structural capability of that particular motor at the particular time will be evaluated. Subscale and partial motor analogs and analytical results must be adjusted to obtain agreement with the full-scale unit. This assumption is based on the premise that a completely successful overtest is achieved. Moreover, it depends on a reliable correlation between analogs and full-scale units.

A second basic assumption is that the subscale and partial-motor analog tests supported by a minimum number of full-scale overtests are sufficient to provide failure levels versus age. To accomplish this it must be possible to differentiate between effects relating to differences in motors (such as with different lots of propellant) and those resulting from age.

The overtest results are obtained for each motor subset at selected test frequencies over a period of time. The results will be available from partial motor analog tests in terms of probability of failure at particular motor ages by each of the principal failure modes. In principle, it is possible to extrapolate the failure probabilities beyond the age range of the data by statistical methods for manipulating data. This approach depends upon past results to define expected trends in future results. Therefore, changes in trends cannot be accounted for. Furthermore, it is very difficult to project over a 10- to 20-year period based on results obtained in the first year or two. It is recommended that analytical techniques be applied along with accelerated aging mechanical properties data to predict the aging trends. These trends should then be used to extrapolate the mean values of overtest results in aging time to determine when the motors are no longer acceptable for service. Since the reliability of different motor subsets will be known at increasing age, it is statistically possible to predict, based on the aforementioned extrapolations, the reliability as a function of time of a particular subset of motors or the total motor population.

The interpretation of the overtest program is aided by recognition of the primary objectives of each of the principal elements of the program which are briefly summarized below:

(1) Full-scale motor overtest - A basis for development and evaluation of the analog devices

(2) Motor Analogs - To provide failure data representative of particular subsets of motors with respect to age-critical failure modes (lots) and aging times

(3) Analysis - A means of defining the analog design, planning the overtest program, and establishing trends for extrapolation of failure results

Each element of the overtest/predictive surveillance program is to be interpreted in light of these objectives.

F. PROPELLANT CHARACTERIZATION

Mechanical characterization of the propellant is required to determine the exact properties of propellant used in the analog and full-scale motors. The data are necessary for analyses to evaluate the adequacy of the analog devices in the analog development portions of Phase II. Provisions should be made for data to support analyses of all specific full-scale motors and motor analogs at various aging times. Analyses of this type may be required to assure that the relationship between motor failure load and analog failure load which is established early, and perhaps checked with a small number of full-scale tests later in the aging program, is maintained with age.

The properties are to be obtained from sectioned full-scale motors and special characterization castings. A sectioned plan must be defined for the motor. The characterization castings should be identical to those used in preparing the analog devices or, if that is not possible, they should be prepared at the same time and should follow the same procedures as much as possible.

It is not possible to define a general sectioning plan that would be applicable to all motors. It will be necessary to obtain test samples from locations in the motors that have not been damaged by the overtest. Therefore, it is mandatory that the low-strain regions of the motor be used for full-scale motor characterization tests. As a general guide, Figures 6-2A and 6-2B depict a sectioning plan for the Minuteman II, Stage III motor.

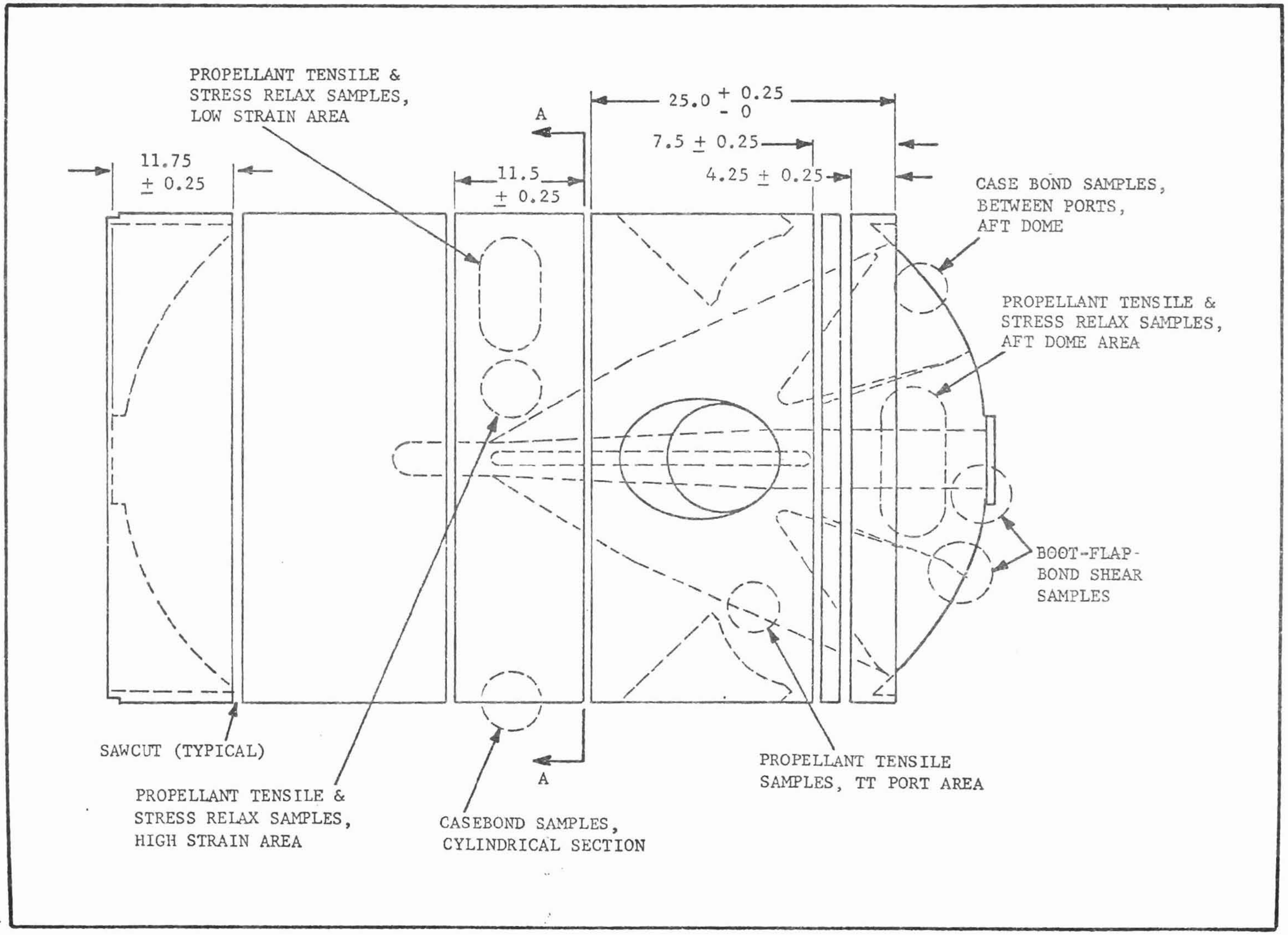


Figure 6-2A. Minuteman Third Stage Sectioning Plan

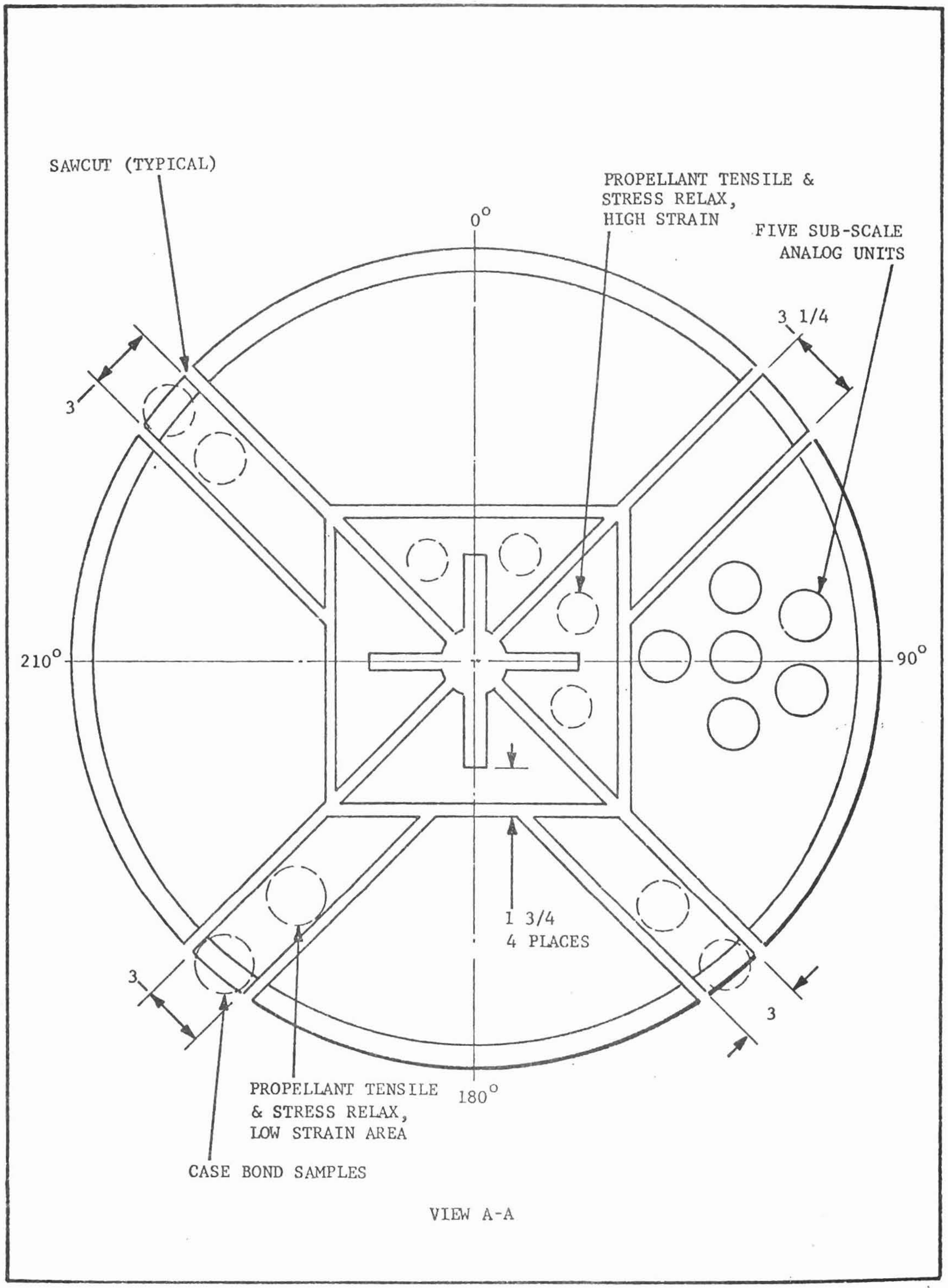


Figure 6-2B. Minuteman Third Stage Sectioning Plan

If the overtest and service life program is directed at motors that are no longer in production, the only source of propellant is likely to be motors withdrawn from the force. Therefore, subscale analog devices as well as characterization specimens must be prepared from propellant taken from the full-scale motor.

Table 6-2 describes the test matrix for characterization of propellant removed from the full-scale motor and for characterization of propellant used in the manufacture of subscale devices. The table also identifies tests that should be performed at certain aging times when neither analog nor full-scale tests would be performed. The objective of these intermediate tests is to provide a surveillance check between test periods. Table 6-2 also includes recommendations for a limited characterization program on propellant subsets not covered by analog testing. Included with the test identification and number of tests is an explanation of test frequency and purpose of the tests.

It is assumed that unaged propellant mechanical properties will be available from a general characterization program performed during development. That program should project the effects of particular environments on unaged propellants. It is further assumed that an accelerated aging program consistent with the current state of knowledge will have been completed or will be underway to support the interpretation of overtest results.

G. ANALYSIS

State-of-the-art analysis methodology[1] should be applied to define critical failure modes in the motor, analyze the motor analog articles and relate them to the real motor, and to perform analysis of aged motors based on predicted properties. The analysis method should be kept the same throughout the aging program. If significant advancements in analyses are made, they should be incorporated in addition to the baseline approach, or all previous analyses should be repeated. This is required to keep the extrapolation procedure on a common basis.

A theoretical analysis based on the properties predicted by accelerated aging models should be performed covering the period up to the time when unacceptable performance is predicted, or for the specified service life whichever is shorter. In performing the analysis it should be recognized that the applied loads (e.g., P-t) may change with age as well as the properties. The accelerated aging analysis is used to determine trends in failure loads for extrapolation of the overtest results.

Statistical analyses of the overtest results and the indicated trends should be performed to provide service life results in terms of reliability versus motor age and accounting for lot differences.

TABLE 6-2

PROPELLANT PHYSICAL TEST MATRIX SIX-YEAR OVERTEST MOTOR (S/N 33348)

Sample Area/ Material	Property	Test Conclusions			Type of Specimen	Number of Specimens	Purpose
		Temperature (°F)	Pressure (psi)	Rate or Displacement (in./min or % Strain)			
High Strain Area/Propellant	Relaxation Modulus	70 20	Ambient Ambient	1% 1%	Stress Relax "	2 1	Required for analysis effect of overtest
	Tensile Failure	70 70 70 70 70 70	600 600 600 600 300 600	2 ipm 20 ipm 200 ipm 2000 ipm 2000 ipm 13.6 ipm	Uniaxial Tension " " " " Biaxial strip	2 2 2 2 2	Failure criteria required for analysis; effect of over-test
Low Strain Area/Propellant	Relaxation Modulus	70 20	Ambient "	1% 1%	Stress Relaxation "	2 1	Required for analysis
	Tensile Failure	70	300	0.2	Uniaxial Tension	2	Failure criteria required for analysis
		77	Ambient	2		2	Compare with lot acceptance data

TABLE 6-2 (Cont)

PROPELLANT PHYSICAL TEST MATRIX SIX-YEAR OVERTEST MOTOR)S/N 33348)

Sample Area/ Material	Property	Test Conclusions			Type of Specimen	Number of Specimens	Purpose
		Temperature ($^{\circ}F$)	Pressure (psi)	Rate or Displacement (in./min or % Strain)			
Low Strain Area/Propellant	Tensile Failure	77	300	2		4	Failure criteria required for analysis
		70	600	2		4	
		70	600	20		2	
		70	300	20		2	
		70	300	200		2	
		70	600	200		2	
		70	300	450		1	
		77	300	450		8	
		70	300	700		2	
		70	300	2000		2	
		70	600	2000		2	
		70	600	1.2	Biaxial Strip	3	
		70	600	13.6		4	
		54	600	13.6		4	
		70	300	300		7	

TABLE 6-2 (Cont)

PROPELLANT PHYSICAL TEST MATRIX SIX-YEAR OVERTEST MOTOR (S/N 33348)

Sample Area/ Material	Property	Test Conclusions: Temperature (°F)	Test Conclusions: Pressure (psi)	Test Conclusions: Rate or Displacement (in./min or % Strain)	Type of Specimen	Number of Specimens	Purpose
TT Port Area/ Propellant	Tensile Failure	77	Ambient	2	Uniaxial Tension	2	Compare with propellant lot acceptance data
		77	300	2		4	Study effect of superimposed pressure
		77	Ambient	20		2	Failure criteria required for analysis & direct comparison with LRSLA data
		77	300	20		2	
		77	300	200		2	
		77	Ambient	200		4	
Aft Dome Area/ Propellant	Relaxation Modulus	70	Ambient	1%	Stress Relaxation	4	Required for analysis
		20	Ambient	1%		2	
	Tensile Failure	70	600	2	Uniaxial Tension	2	Failure criteria required for analysis
		70	600	20		4	
		70	300	200		2	
Aft Dome Area/Boot-Flap Bond	Bond Shear Strength	70	Ambient	0.2	Bond Shear Specimen (w/o Propellant)	2	Criteria for secondary failure mode
		70	Ambient	2.0		2	
		70	300	2.0		3	
		70	Ambient	20.		2	
		70	300	20.		2	
		70	600	20.		2	
		70	Ambient	200		3	
		70	600	200		2	
		70	300	2000		3	

TABLE 6-2 (Cont)

PROPELLANT PHYSICAL TEST MATRIX SIX-YEAR OVERTEST MOTOR (S/N 33348)

Area/ Material	Property	Test Conclusions			Type of Specimen	Number of Specimens	Purpose
		Temperature (°F)	Pressure (psi)	Rate or Displacement (in./min or % Strain)			
Aft Dome/ Case Bond	Case Bond Shear Failure	70	600	2	Case Bond Short Shear Specimen	3	Failure criteria for secondary failure mode
		70	Ambient	20		2	
		70	300	20		7	
		70	600	20		2	
		70	300	200		6	
		70	Ambient	2000		3	
	Case Bond Tensile Failure	70	1000	20	Case Bond Tensile Specimen	3	Failure criteria for secondary failure mode
		70	300	20		2	
		70	300	200		2	
		70	600	200		3	
		70	600	2000		2	
Cylindrical Section/	Case Bond Tensile Failure	70	1000	20	Case Bond Tensile	1	Failure criteria for mode
		70	300	200		1	

H. INSTRUMENTATION

Considerable effort has been expended in the area of propellant grain instrumentation. References 3, 4, and 5 include explanations of the state-of-the-art for particular gages up to 1972. Additional work is being conducted under the C-4 program and in the RPL program, "Development of Improved Normal Stress Transducers for Propellant Grains" (UTC). The instrumentation possibilities existing at the time of planning of an overtest should be reviewed to determine which methods best fulfill the requirements of the particular test.

Much of the recent work on instrumentation development has been directed at embedded transducers. For motors or analogs that are manufactured especially for an overtest program, it may be possible to incorporate these developments to advantage. However, for motors that are already built, the instrumentation is limited to that which can be mounted external to the case or grain surfaces. The ICBM overtest program was thus limited. Therefore, the discussion herein on instrumentation apply to externally mounted (to the grain) instrumentation and generally to pressure testing.

The major instrumentation challenge is finding a method for detecting grain or case-bond failures during high-rate loading. Location of the gage can be critical. A lag in response such as may result if a gage is located an appreciable distance from the location of failure may cause misleading results and errors in interpretation.

Failure detection is made difficult by not being able to incorporate instrumentation applicable to failure detection at the time of manufacture. Although grain failure has been observed repeatedly using only external instrumentation, this area of overtest technology should be given high priority and gage redundancy should be incorporated into the tests. Instrumentation plans should recognize potential failures other than those postulated.

In the following discussion consideration is given first to gages for use inside the grain cavity. These are linear potentiometers, leaf deflectometers, pressure gages, strain gages, event gages, and LVDT's. Following these a discussion is given of instrumentation for use on the exterior of the motor case, including strain gages, linear potentiometers, LVDT's, and through-the-case gages.

This section on instrumentation applies in varying degrees to both the subscale and full-scale motor overtests. It will be referred to in the presentation of the analog test program, Paragraph I, and in the full-scale overtest program, Paragraph J.

1. Instrumentation for Use Inside the Grain Cavity

a. Linear Potentiometers

Reliable and accurate measurements of cavity deflection may be obtained by the use of linear potentiometers. Special bracketry can be fabricated to mount potentiometers in most grain cavity locations.

Special potentiometers must be fabricated for use in areas where the expected deflection is equal to or greater than 4/10 of the initial cavity dimension. If the expected deflection is larger than 3/4 of the initial dimension, linear potentiometers cannot be used.

Potentiometers are restricted to locations where they will not be exposed to large fluid impact forces resulting from the pressure transient, i.e., no gages can be installed in the center core if the motor is to be pressurized through a centerport.

An electrically nonconductive fluid (gas or mineral oil) must be used to pressurize the motor, or linear potentiometers will short out.

All linear potentiometers must be provided with pressure relief holes through the gage case to prevent gage crushing or a false retraction of the gage.

If gages ae to be mounted in a highly stressed (or strained) area, the mounting bracketry must not create a stress concentration sufficient to cause appreciable stress concentration. For example, if a gage is bonded to the propellant in a circular centerport, grain cracking will preferentially occur next to the bond between the propellant and the bracket.

In addition to the linear deflection that is to be measured, angular deflections of grain surfaces must be considered in bracketry design. (See Figure 6-3 for the effect of angular deflection.) Figures 6-4 and 6-5 illustrate a linear potentiometer used to obtain grain deflection in the overtest program.

b. Leaf Deflectometers

Leaf deflectometers can be fabricated to respond to a larger deflection than is possible within linear potentiometers. Applications are not limited to stock gage sizes. Also, leaf deflectometers do not require vent holes since they are not contained in a case. Figure 6-6 shows a leaf deflectometer used in the overtest of a Minuteman II, stage III motor. Although leaf deflectometers have been used extensively in pressure overtests, the demonstrated accuracy and reliability are not as good for linear potentiometers. These deflectometers have a

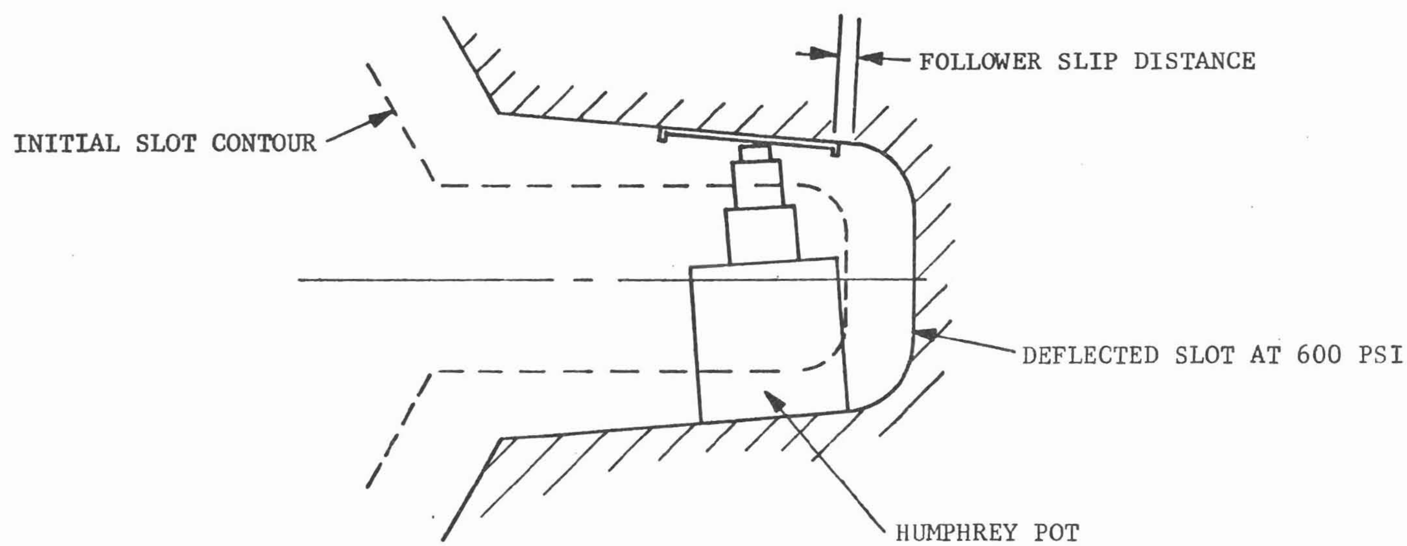


Figure 6-3. Humphrey Rectilinear Potentiometer in Critical Wing Slot

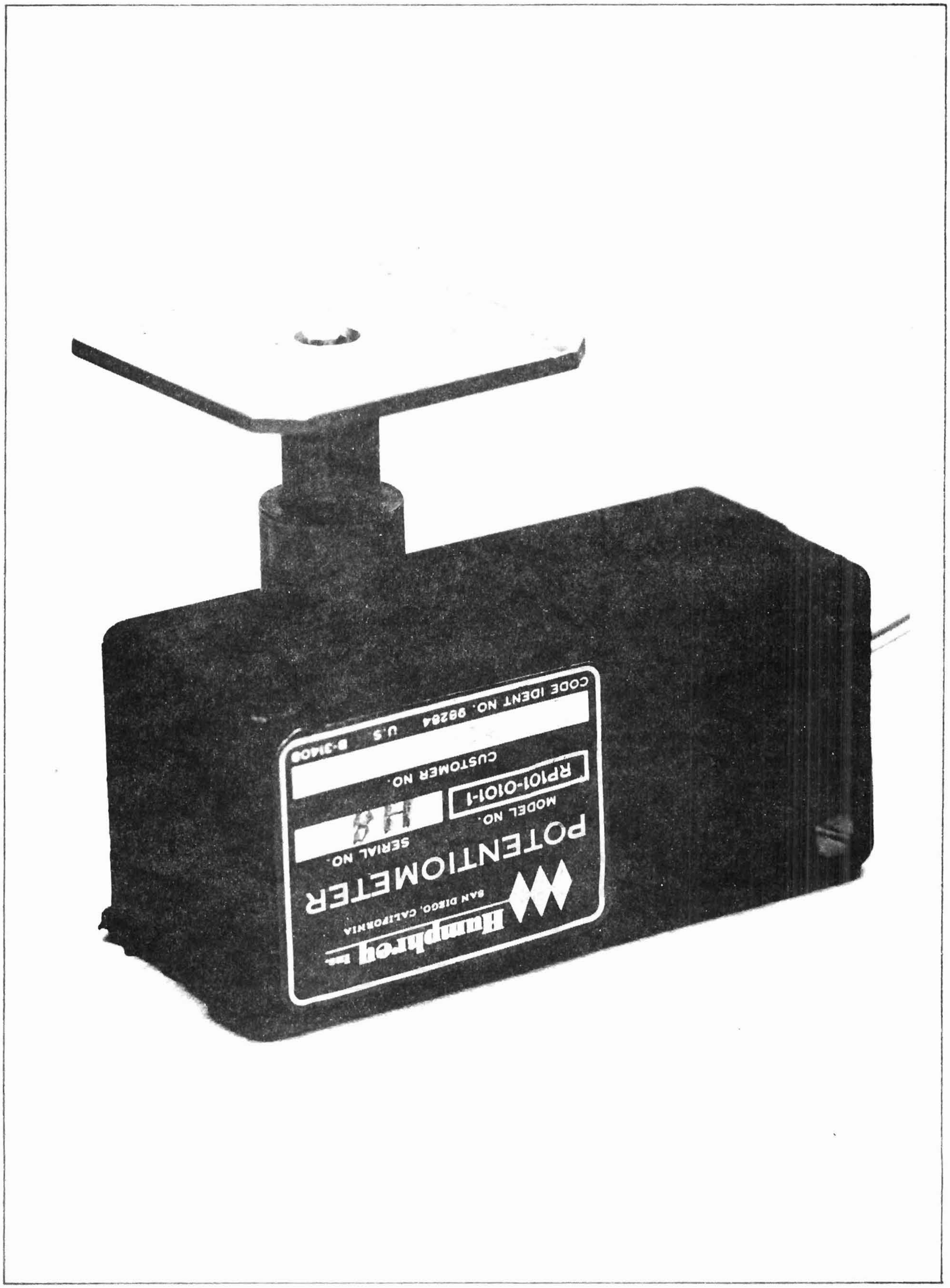


Figure 6-4. Potentiometer Used in Wing Slots

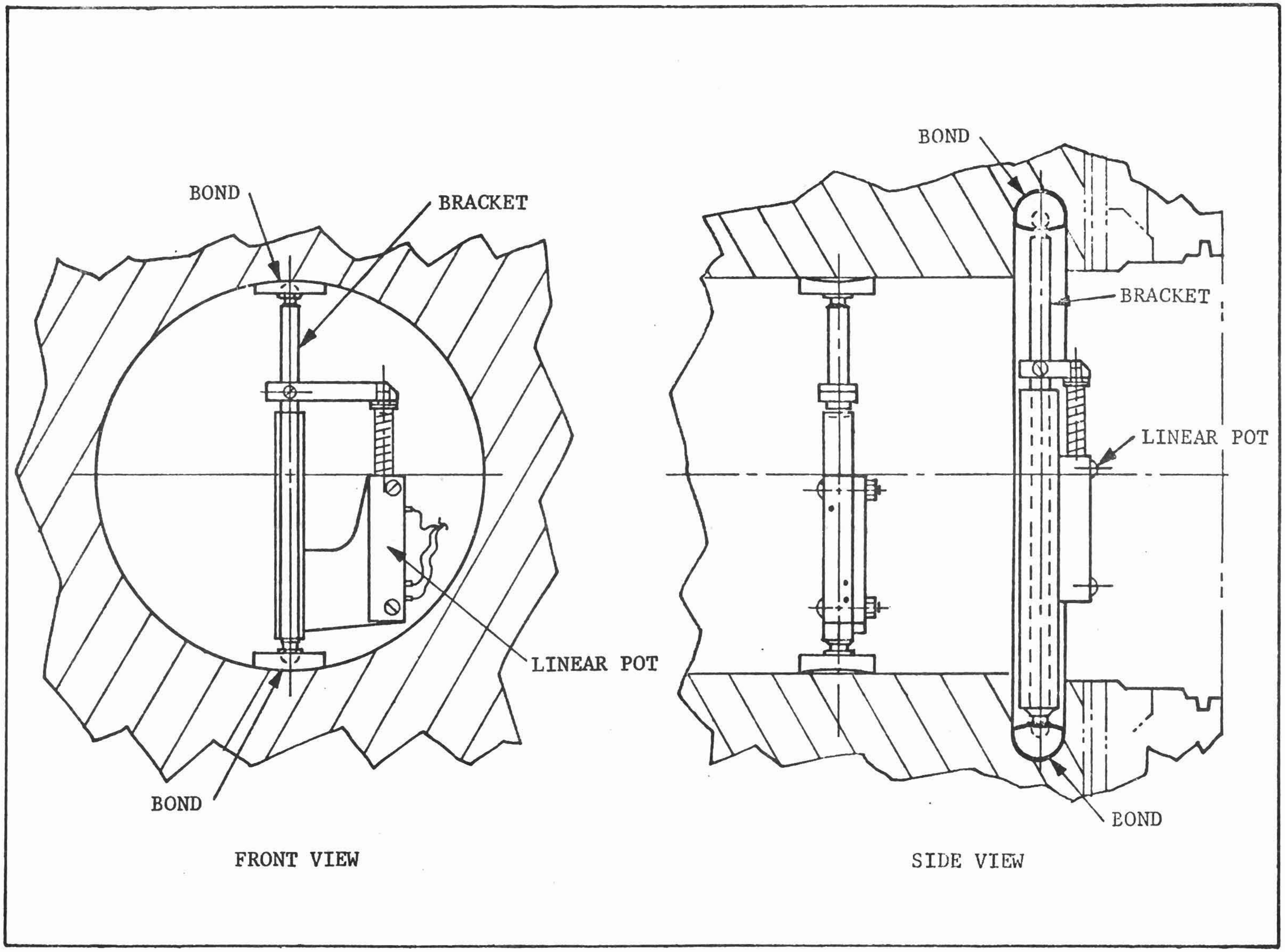


Figure 6-5. Linear Potentiometer Installation

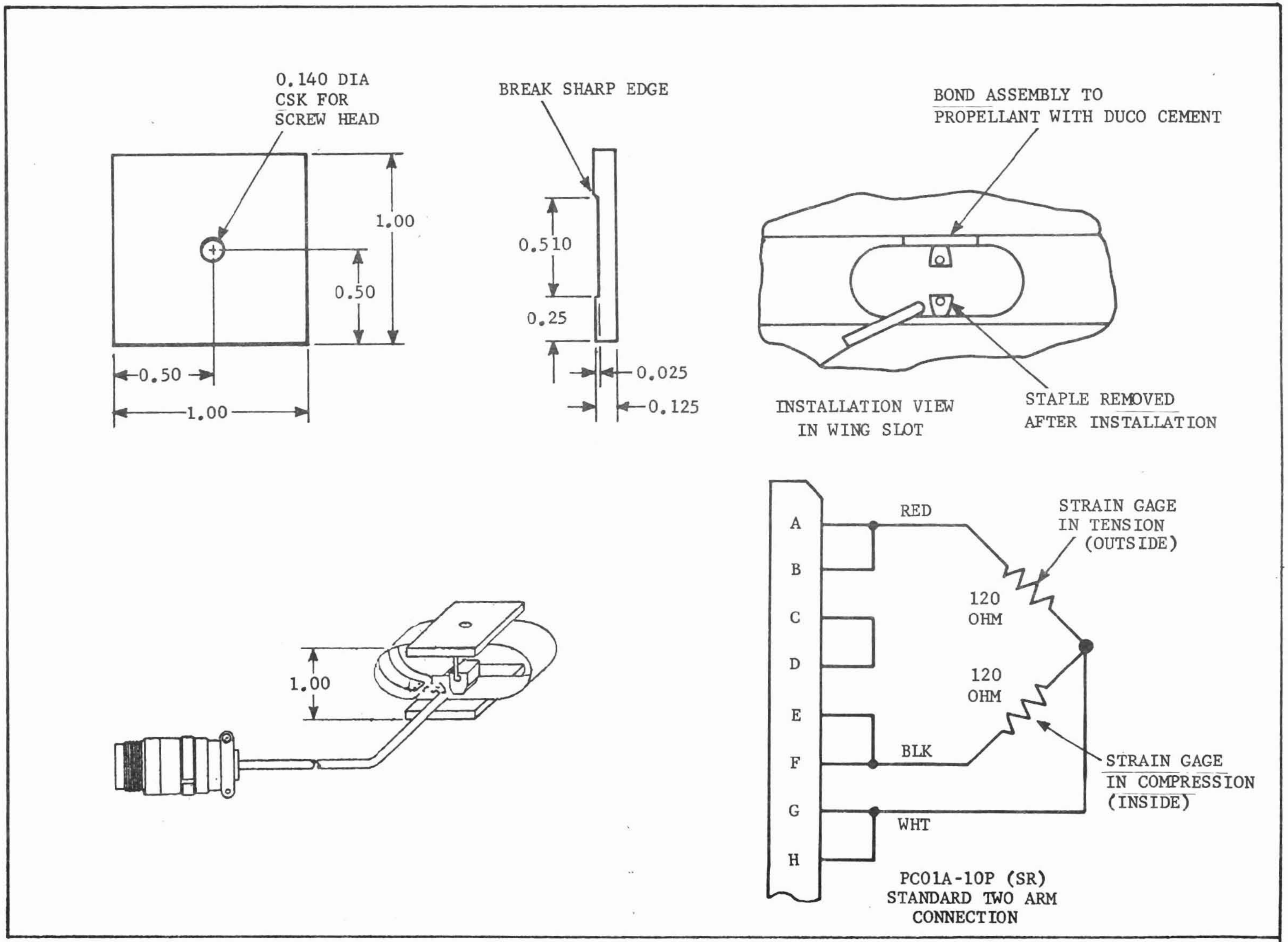


Figure 6-6. Strain Gage Deflectometer

tendency to flutter when exposed to transient fluid flow forces. All other problems applying to linear potentiometers also apply to leaf potentiometers.

c. Pressure Gages

The technology of both crystal-type and strain gage (diaphragm) pressure gages is well advanced and many commercially available articles will serve the needs of a pressure overtest.

Pressure gages should be installed within the motor cavity adjacent to critical failure regions if possible. Especially in large motors, significant pressure drops occur during the pressure transient, so that pressure measured at an end closure may only be an approximation of the pressure within the motor cavity.

The major problem with pressure gages is "ringing" during the high-rate application of pressure. "Ringing" responses have been obtained on all pressure gages used in all high-rate tests. This makes data interpretation quite difficult. Redundant gages are recommended.

d. Event Gages

Event gages have been developed especially for use in detecting grain cracks during pressure tests. Basically, they are conductive coatings with mechanical properties similar to the propellant. The gage cracks as the propellant cracks thus interrupting an electrical circuit.

Event gages have proven to give good failure information, and are reasonably reliable, when used on double-base or composite propellants. Reference 6 includes a report on the development of an event gage for the ICBM overtest program; its application and performance characteristics are described also. Event gages can be installed on any accessible location. The acquisition circuit is simple and well-understood.

Conductive coating event gages must be protected from penetration by the motor pressurizing fluid. Also, gage leadwires must be protected from damage by the fluid flow forces during the pressure transient.

Gage materials have been proven on a limited number of propellants. They have not been used on XLDB propellants.

The connection of the leadwires to the event gage is the most fragile part of the system. Further, the same problems of creating stress concentrations on the propellant (specifically at the leadwire-to-gage connection) exist for event gages as well as linear pots and leaf deflectometers.

e. Strain Gages

Elastomeric strain gages have been considered;[4,7] they show promise for the measurement of propellant strains, although no off-the-shelf device is presently available. Elastomeric strain gages must be individually calibrated and then bonded into place. There is a question as to the stress-concentration effect of the bond between the propellant and the gage.

Neither conventional wire nor foil strain gages are suitable for use on propellant. The effective elastic modulus of these gages is too high relative to that of propellant to avoid discontinuity stresses and unbonding of the gage from the propellant.

f. Determining the Extent of Grain Cracking

This is not instrumentation per se; however, it will be considered here as it is a means of obtaining data which are critical for the interpretation of overtest results.

The use of soluable dye in the pressurizing fluid is the preferred method of determining the extent of grain cracking caused by high-rate testing. Its use has been successfully demonstrated on one motor in the LRSLA program. Extensive dissection of a failed motor is necessary to map the extent of cracking, even if dye is used during the test. Unless exceptional attention is given to ensure that the motor pieces are handled correctly, cracking will be extended during dissection and inspection operations.

Visual and NDT inspection techniques have not been acceptable in the past programs for defining the existence or extent of cracking even in small motors. X-ray of motors after high-rate testing is insufficient to determine the extent of cracking. Dimensional inspection of the grain cavity before and after high-rate testing is insufficient to determine the extent of grain cracking.

g. LVDT's

The LVDT[8] has infinite sensitivity, as opposed to a linear pot whose sensitivity is limited by the size of wire used in the resistance element. The moving portion of an LVDT is inherently pressure-balanced. It can be operated in water or other conductive medium. LVDT's should be satisfactory to replace linear pots in any overtest application. However, there seems to be no history of successful use in a pressurized situation. The effect of pressure on the coil element has not been determined or reported.

2. Exterior Motor Instrumentation

a. Strain Gages

Strain gages are preferred as the external instrumentation to detect propellant grain failure. Although strain gage response to failure is not as positive as that of internal event gages, it is better than internal or external potentiometers. BLH Type PA-3 postyield gages have proven satisfactory for measuring case or dome strains. They also respond to changes in case strains associated with grain cracking.

Strain gage data, especially that obtained on the domes, is not directly of value in verifying the accuracy of the math model used in the grain analysis. They serve primarily as failure event gages.

b. Linear Potentiometers and LVDT's

This is the preferred type of instrumentation for use in measuring deflection at one point on the case relative to another point. Deflection data are usually more applicable to verifying the analysis model than strain gage data.

Measurements made relative to ground (radial chamber deflection, for example) generally include rigid-body motion of the chamber, and, therefore, may be unreliable. Girth band measurements have proved to be less sensitive than case grain gages as event indicators in detecting grain failure.

c. Through-to-Case Gages

Normal stress transducers, either piston or diaphragm type, should be of value in high-rate testing although they have not been proven at this time. They appear to have potential both for detecting grain failure and for verifying the math model for grain analysis.

Consideration should be given to simple failure indicators for special types of critical failure modes. For example, such a failure indicator (a pipe cleaner inserted through a small hole drilled through the dome into the cavity between insulator and shrinkage liner) was successfully used to determine whether or not a particular bonded interface had debonded during test.

I. ANALOG TESTS

1. Design of Analog Devices

Analog devices are essential to a complete overtest program. It is economically impractical to base a complete program on full-scale tests alone. Therefore, analog devices should be used to obtain failure data representative of overtest conditions. They should be performed in sufficient quantity to provide statistical significance to overtest

results. They may also be applied to advantage to verify methods of analysis which are, in turn, used to analyze the motor. Analog devices, particularly those termed subscale motor analogs, are also useful for assessing instrumentation for use in full-scale and analog test programs.

It has been considered herein to be beyond the scope of the overtest program to develop failure criteria for propellants. However, the analog devices considered here, when tested to failure, may be used to evaluate present failure criteria as well as stress analysis techniques.

Partial motor analog devices may be used in a program in development or for analysis of an operational force. In the latter case, test articles are prepared from propellant removed from full-scale motors.

The design of test devices for providing failure data and for verification of stress analyses should be capable of providing structural conditions analogous to conditions in critical regions of full-scale motors subjected to critical loads either singly or in combinations.

Principal loads of concern (see Paragraph C) are:

(a) Internal pressure

(b) Cure and thermal shrinkage

(c) Acceleration (axial and transverse)

(d) Vibration

As a general rule, these are the governing design loads for ICBM motor grain designs although all anticipated prelaunch, launch, and flight loads should be considered in evaluating grain structural integrity. The test must be capable of being performed at different rates as appropriate to the type of loadings. Internal pressure simulation tests must involve high loading rates; acceleration loads are normally at intermediate to low rates (ABM accelerations are an example of exceptions) and thermal loads are usually low rate. The ICBM motors are commonly provided with controlled environments; consequently, the temperature limits and cooling rates are not high. The vibration loads are dependent upon the imposed frequencies and may occur concurrently with another load.

Analog devices must simulate structural conditions at critical locations in the motor under investigation. To ensure similitude, analog devices must duplicate the exact conditions at the critical regions of the motor or conditions must be accurately scaled in the analog devices by maintaining values of significant dimensionless parameters characteristic

of the full-scale unit. The significant dimensionless quantities can be derived by dimensional analysis taking into consideration the various physical quantities affecting the problem (Reference 1).

Regions of concern that often occur in ICBM motors are classified in the order of importance as follows:

(a) Flap (shrinkage liner) terminations

(b) Propellant bond terminations (on dome or cylinder)

(c) Adapter tip concentrated strain regions (glass-epoxy cases with propellant bonded to domes)

(d) Bore surface on circular port grain designs

(e) Slot tips in slotted-bore designs

a. Partial Motor Analogs

Test specimens which simulate bond terminations, flap terminations and adapter tip strain regions have been used in ICBM development programs.[9] Using this approach, the same analytical methods are applied to the design of the sample as is used for the region of the motor being simulated. Local design features, such as insulator, propellant, termination geometry, etc, are made identical or scaled to the motor. The stress-strain condition in the sample is adjusted by varying the method of loading or geometric parameters of the test specimen. Loading is ordinarily accomplished by conventional laboratory equipment. The specimen is judged to represent the critical region of interest in the motor when the stress-strain conditions, determined by the analysis, are equal. The success of this approach depends upon being able to vary enough parameters to achieve the desired simulation. The response of the test specimen to loading and the time of failure initiation can be determined more definitely than with usual methods of instrumentation required in analog and full-scale motors because the desired information can often be determined by direct observation.

The validity of the analysis is evaluated on the basis of comparison of strain (deformations) measured in the specimen tests and those calculated in the specimen for the particular set of loading conditions. If the analysis is verified by the specimen results, it is considered acceptable for analysis of the motor region being simulated. By loading the specimen to failure, the allowable stress-strain condition for the region of interest is determined. The failure prediction thus obtained is consistent with the analysis approach and does not depend upon a precise knowledge of such undefined considerations as nonlinear behavior or failure criteria. Furthermore, combinations of loads can be rapidly studied.

Hercules has achieved success with the partial-motor simulation approach in development programs. Critical stress regions of motors which contain composite and double-base propellants were simulated with analog samples representative in cross section of flap terminations and bond terminations. Agreement was achieved between test and analytical results and analytical predictions for the full-scale motor and the analog device.

Figures 6-7 through 6-10 illustrate some typical partial motor analog devices that have been used by Hercules. A current AFRPL program should provide additional data on the design and application of this type of device.

There are various other devices which may be considered as analogs of specific motor conditions. The biaxial-strip test is a reasonable representation of the centerbore stress condition and propellant stresses in the vicinity of bond terminations. The poker chip test is an analog of case-bond areas removed from termination regions. The scarf joint test is an attempt at an analog of case-bond termination regions in that it provides a condition of shear plus tension; however, the shear plus triaxial tension condition does not reasonably simulate any region of a real motor. Various other test devices provide data under various states of stress none of which simulate actual motor stresses but which collectively provide failure data on state-of-stress effects useful in motor strength analysis.

Table 6-3 presents some of the possible partial motor analog devices that have been used to varying degrees in motor grain analysis. The failure modes to which they have been applied are listed also.

b. Subscale Motor Analogs

A subscale motor analog should provide the types of information normally desired from a structural test vehicle (STV); namely, (1) an evaluation of the analysis techniques, and (2) an experimental analysis of the motor design and structural integrity which supplements the theoretical analysis. The critical stress and strain conditions existing in the real motor must be simulated. The design should be suitable, with minor modifications, for testing under a variety of loading conditions. It should be large enough to allow for adequate instrumentation yet not be prohibitively expensive or difficult to handle. If possible, it should be small enough to permit storage of several units for future testing in an aging program. Boundary conditions and residual effects from casting or manufacturing which are peculiar to the scaled motor but not the real motor should be known or eliminated if possible. As is shown in the following discussion, it is necessary to compromise some of these objectives.

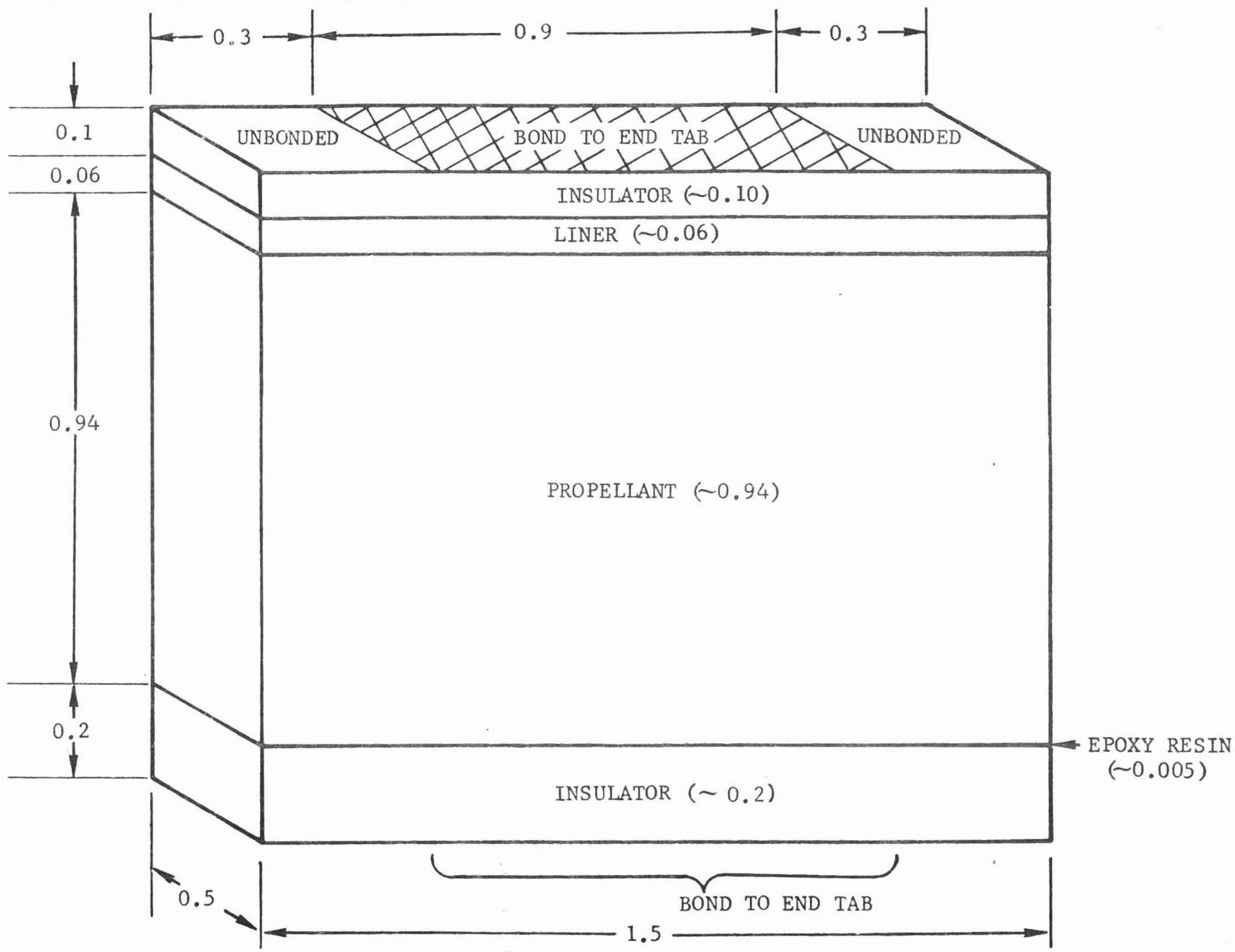


Figure 6-7. Casebond Analog Sample

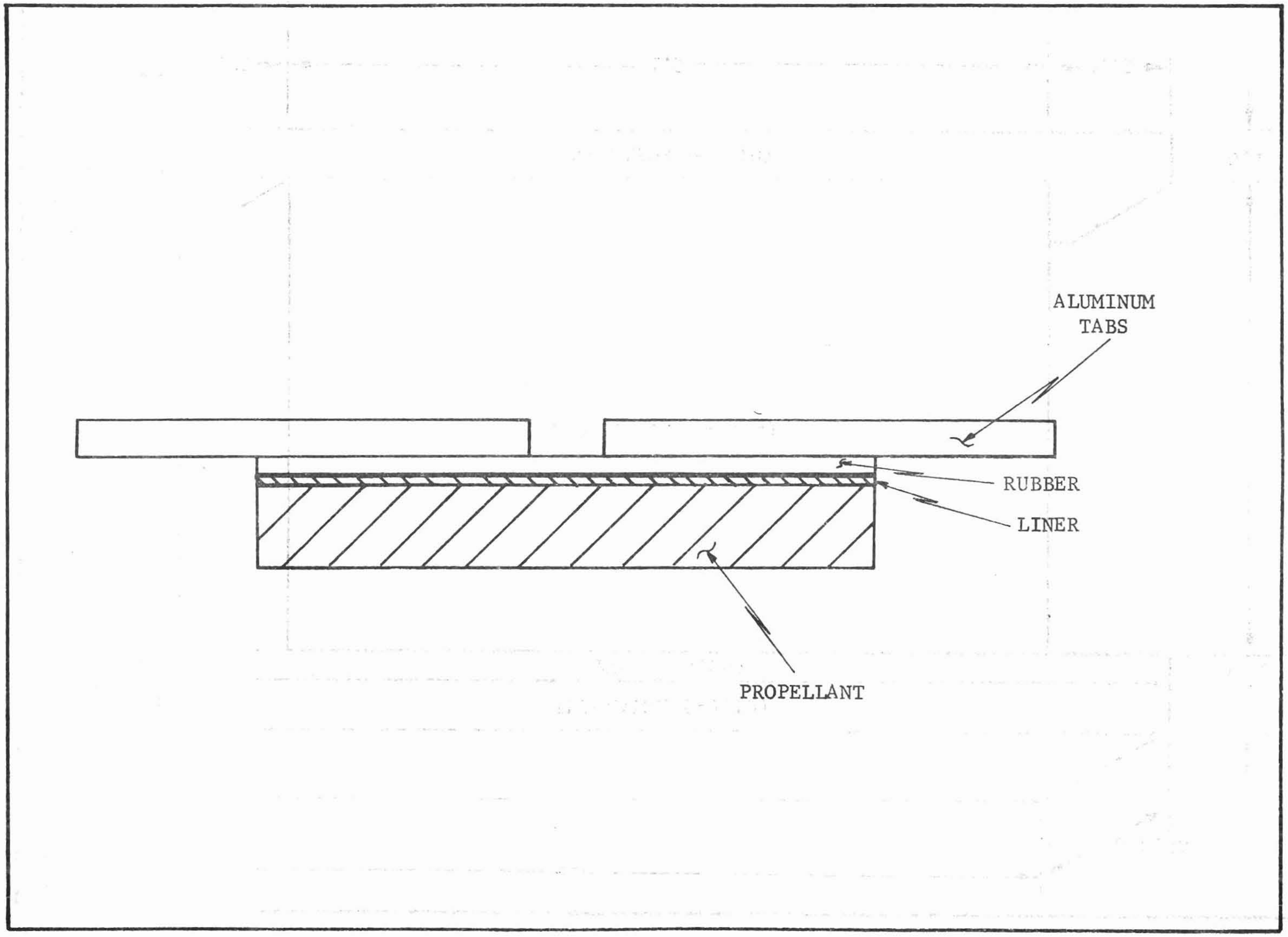


Figure 6-8. Candidate Partial Motor Analog for FM 7

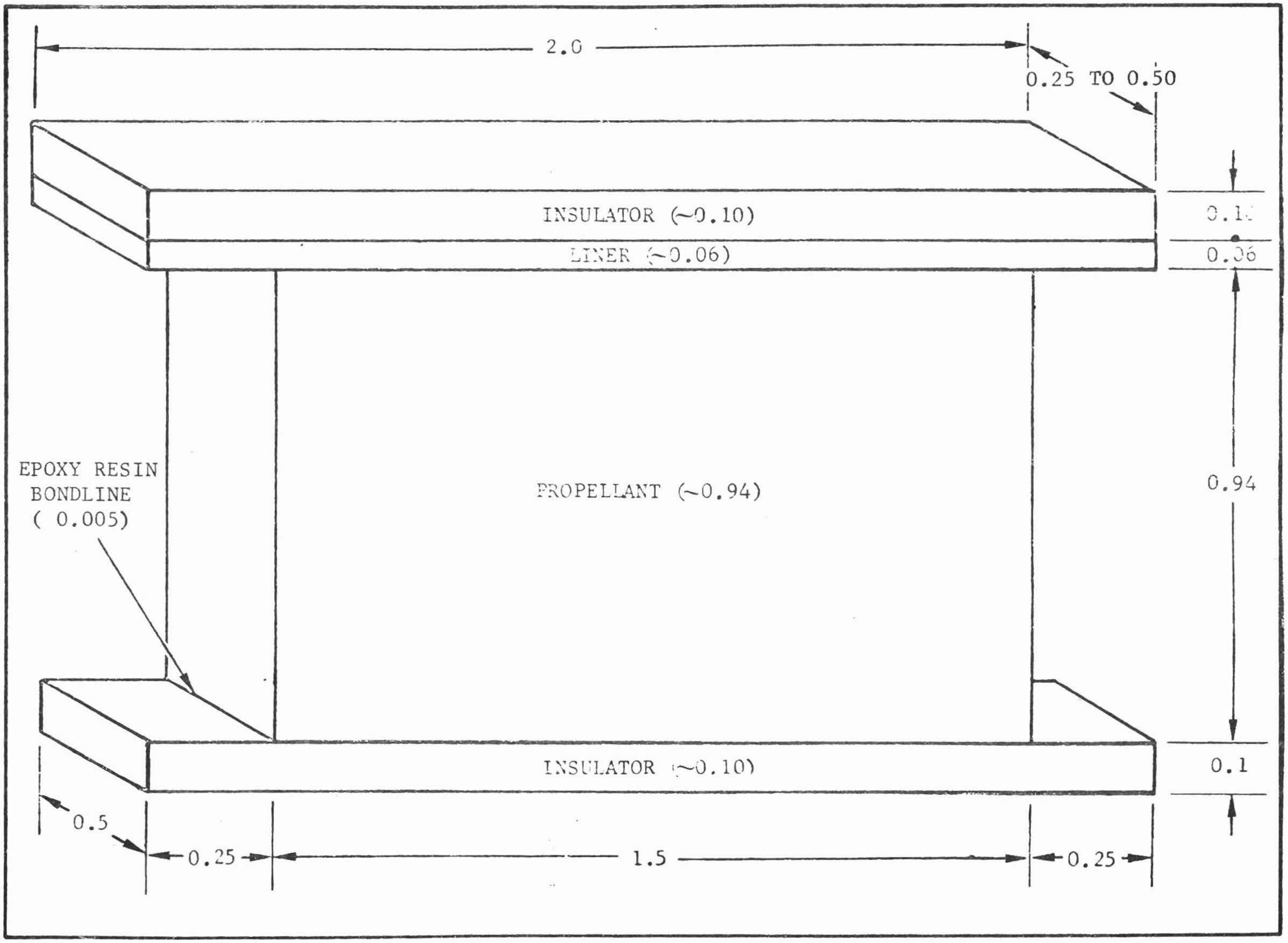


Figure 6-9. Discontinuity Analog Sample

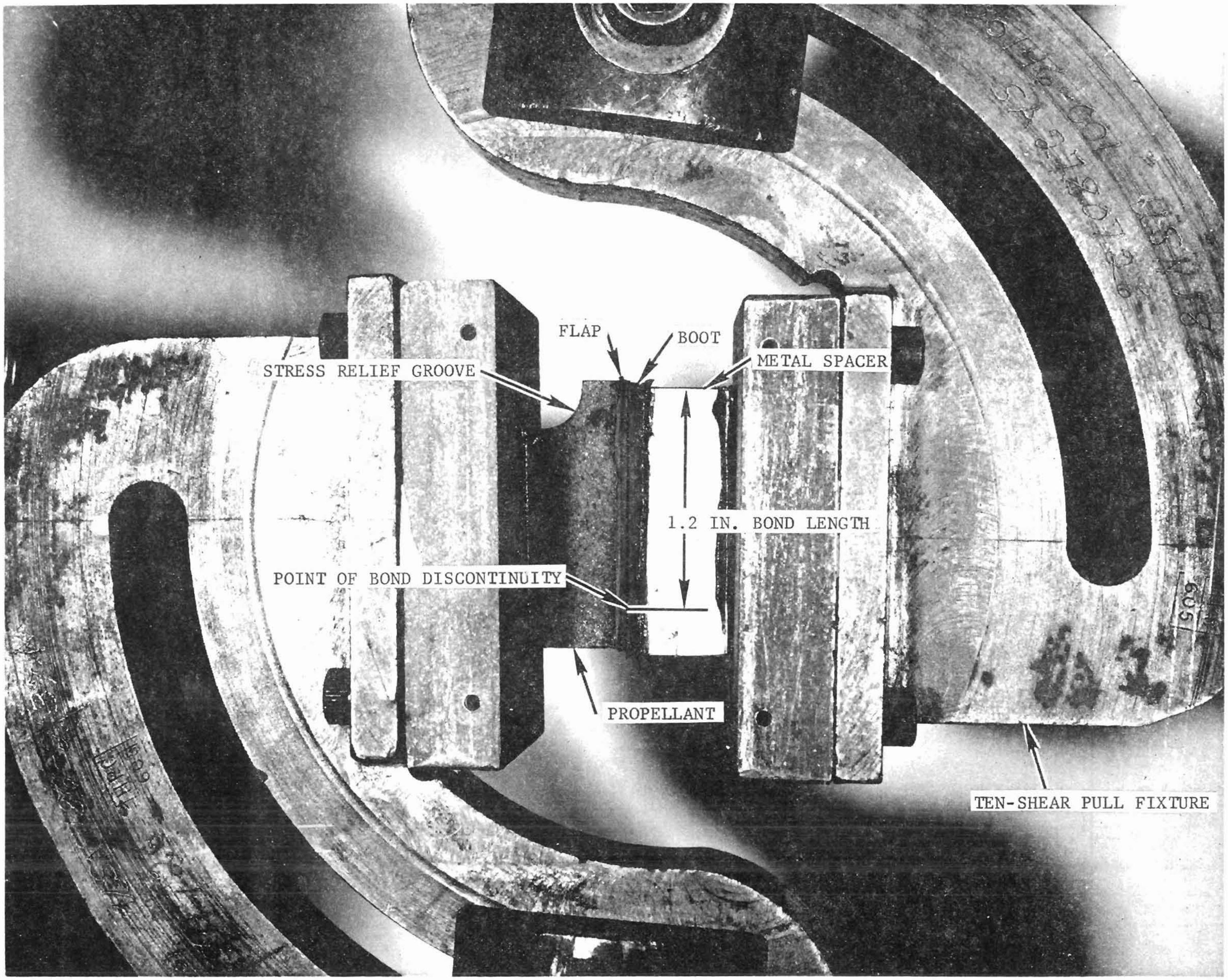


Figure 6-10. Partial Motor Analog for Boot-Flap Failure

TABLE 6-3

PARTIAL MOTOR ANALOGS

Analog Type	Failure Mode
Biaxial strip	Centerport cracking during storage
Biaxial strip plus superimposed pressure	Centerport cracking during ignition
Biaxial strip with center crack	Crack propagation
Biaxial strip with elliptical center hole	Void cracking during storage
Biaxial strip with center crack plus superimposed pressure	Void-induced cracking during burning
Poker chip	Casebond failure during storage
Case bond analog (Figure 6-7)	Casebond failure during storage
Uniaxial tension	Grain collapse during ignition
Flap termination case bond sample (Ref 9)	Flap termination casebond failure under pressure
Adapter tip analog (Figure 6-8)	Casebond failure at adapter tips
Discontinuity analog sample (Figure 6-9)	Right angle bond termination failure
Bond discontinuity sample	Boot-flap failure under shear, axial stress, and pressure

The first problem is in dimensionally scaling the full-scale motor such that conditions are simulated in the subscale unit. Conventional laws governing dimensional analysis reveal that this is not a good approach to simplification of the problem. The first rule of dimensional analysis governs the number of dimensionless parameters which must be duplicated in scaling from one model to another. The number is equal to the difference between the number of physical quantities affecting the problem and the number of fundamental dimensions. In the majority of structural problems there is an abundance of significant physical quantities, but only two fundamental dimensions (e.g., force and length). For the more general problem, for instance, transient thermal stress in a viscoelastic material, one can add only two more fundamental dimensions, temperature and time. Following the Buckingham Pi theorem, it can be shown that the transient thermal stress problem required nine different nondimensional parameters for scaling. It is impossible to scale for equivalency of transient thermal stress over a finite time period at a single point in the simpliest of motor configurations. However, for a complete subscale analog of a motor, it is necessary to simulate conditions at several critical locations. Even if the transient thermal problem is excluded, this is difficult to achieve for general loading requirements.

A lower limit on physical dimensions is imposed based on instrumentation. The critical region being instrumented for study in a subscale unit must be large relative to the measuring device. It is usually desirable to instrument full-scale motors and analog devices with the same types of gages. However, the critical region of the subscale units are reduced relative to the full-scale unit in proportion to the dimensional reduction of the subscale unit. The gage size cannot be scaled downward; therefore, the gage size relative to the size of the critical region is greater in the analog. Since the gage will indicate an average value over a finite length and strains/stresses are normally rapidly varying in the critical regions, different results are to be expected from the gages. The difference in results should increase as the difference in analog motor and real motor size is increased.

Some of the more critical problems are dependent upon actual physical dimensions and cannot be scaled. For example, in a fiberglass case the propellant strains near the polar adapter (bonded domes) depends upon the amount of fiberglass outward motion relative to the adapter and not upon the local case strains. It may be impossible to obtain equivalent relative deflections in a subscale motor although the strains are duplicated. To simulate actual fiberglass, outward deflections at the adapter would impose unacceptable strains on the material.

An additional constraint is imposed if the identical case material is to be used. Due to the high strength of filament-wound chambers, they can be made relatively thin even in large diameters. To obtain equal case strains at equal load as the diameter is reduced

requires that the case be made thinner. A point is reached at some critical diameter that the case thickness becomes less than the thickness of a layer of fiberglass. At that point, of course, the unit becomes impossible to build. Use of the same identical case material is not absolutely necessary if material modulus and thickness are scaled in inverse proportions to one another.

It is desirable to duplicate the deformation characteristics of the domes to simulate critical propellant strain conditions in propellant grains which are bonded to the domes. The growth characteristics of a filament-wound case dome depend upon the filament winding pattern and dome shape. Proper filament-wound case design requires careful matching of winding angle and dome shape to ensure a balanced structure. The winding angle and thickness varies with radial position over the dome with a maximum angle of 90^{o}, relative to the motor axis, and maximum thickness occurs at the glass termination point on the polar adapter. Elastic constants such as modulus and Poisson's ratio are different in different directions as well as at different locations. Therefore, to simulate a domed motor exactly requires an exact scale-down of the dome shape and the use of exactly the same winding angle as the full-scale motor. Use of anything other than the correct dome shape or winding angle will give misleading results. This is particularly true near the dome-cylinder-skirt junction where due to the local increased stiffness and abrupt change in geometry the dome ordinarily rotates during pressurization relative to the skirt. In many fiberglass motors the dome deflection may be inward upon initial pressurization and outward as the dome assumes a new shape and pressure is increased. Unfortunately, in many motor designs, the dome is a critical region of the grain design.

The necessity for the type of attention to detail presented in the preceding discussion will contribute greatly to costs of thoroughly-scaled motor analogs. Mandrels must be made for winding of the cases (including the skirts); and consideration must be given to incorporating insulators, flaps, etc, which adequately represent these components in the full-scale motor. In summary, development of an accurately scaled-down filament-wound motor case is not greatly different from development of the real case.

Most of the desirable features of a complete analog motor can be achieved in a cylindrical unit. (See Figure 6-11.) Conditions in the dome are not geometrically simulated, but the significant conditions of tension plus shear can be simulated by varying the bond termination design parameters on the end of the cylindrical unit. Stress/strain fields at the end are made similar to the full-scale dome bond termination point by matching analytical results in the analog and full-scale motor. Conditions at all other locations (i.e., cylindrical flap termination and centerbore) are scaled from the full-scale unit using conventional scaling laws.

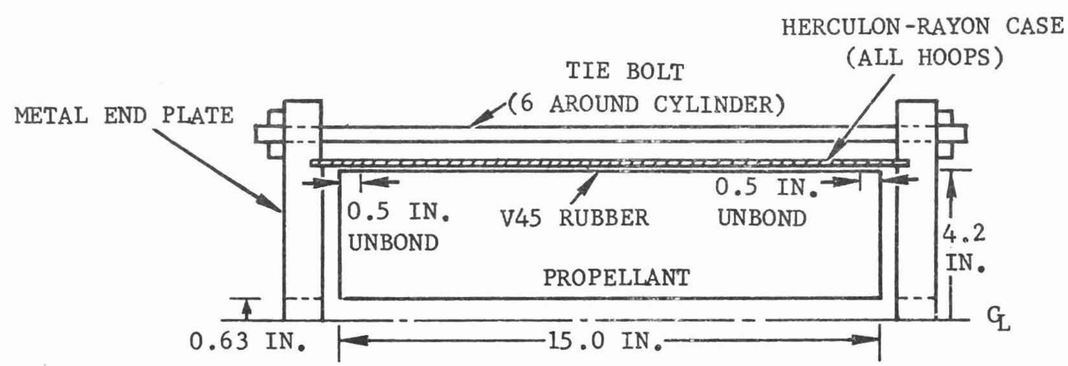


Figure 6-11. Cylindrical Motor Analog

Three subscale motor analog test vehicles are shown in Figure 6-12. Fundamentally, the units are very similar. Failures are achieved according to plan by varying basic structural parameters such as length-to-diameter ratio, flap length, liner thicknesses, case thickness, flap length, and web fraction. Voids and cracks or slotted designs can be introduced without significantly changing the basic units.

Since the ICBM Overtest Technology Program emphasis was directed at the centerport cracking mode, specific details are provided for the centerport cracking cylinder (CCC) test vehicle only. Information presented here should be used as a guide only as specific design details will depend upon the particular motor application.

As was demonstrated in the subject program, the CCC can be cast, manufactured by machining from full-scale motors, or machined from cast propellant slugs. Thus, they are applicable to operational or development motors.

The CCC is a pressure analog unit designed primarily for studies of the bore cracking failure mode. The basic unit can be extended with slight or no modification to long-term shrinkage or case-bond failure (bore or flap terminations) modes. By introduction of subsurface voids or cracks the unit can be applied to fracture mechanics studies. Three pressure analog configurations are shown by Figures 6-13 through 6-15.

Two of the configurations are applicable to a wing slot cracking failure mode and one applies to an aft centerport debonding failure mode. All three models are generally similar to centerport cracking cylinders which have been previously used for failure theory analysis.[10] The models consist of cartridge-loaded propellant grains in filament-wound cases. Heavy metal end plates are bonded onto the ends of the grain, and the entire assembly is held together with tie bolts. The differences between the three types of models is achieved with various centerbore designs. One model to test the wing-slot cracking-failure mode had a circular centerbore, and the other was a star grain configuration of four shallow slots.

High-rate pressurization rates have been achieved in loading these models to failure. Models were instrumented with strain gages on the case and with event gages for detecting propellant cracking on the grain bore surfaces. Measured pressure at which model failure occurred was in good agreement with analytical predictions.

To achieve grain cracking as desired, it is necessary to produce high centerbore strains without first inducing other failure modes. A flexible case is, therefore, desired to allow high centerport strains. This can be accomplished with a low-modulus, high-strength case material and/or a thin case. Very thin cases are not expected to be reliable enough due to the accuracy limit of the manufacturing techniques.

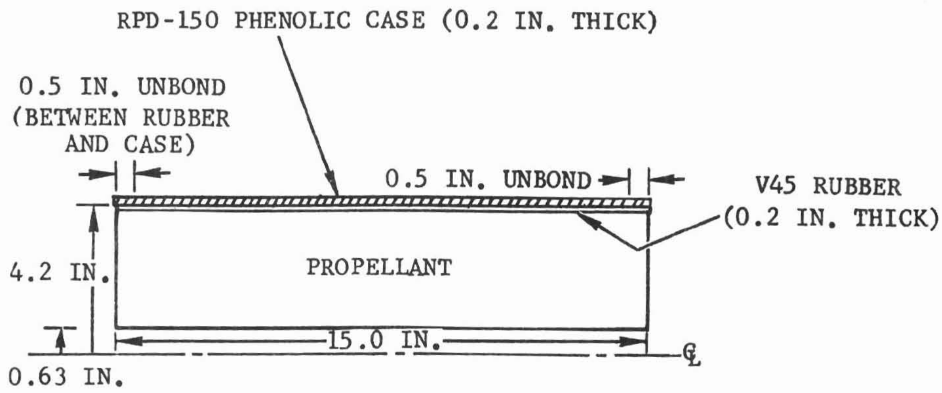


Figure 6-12a. Motor Analog for Centerport Cracking Due to Thermal Loading

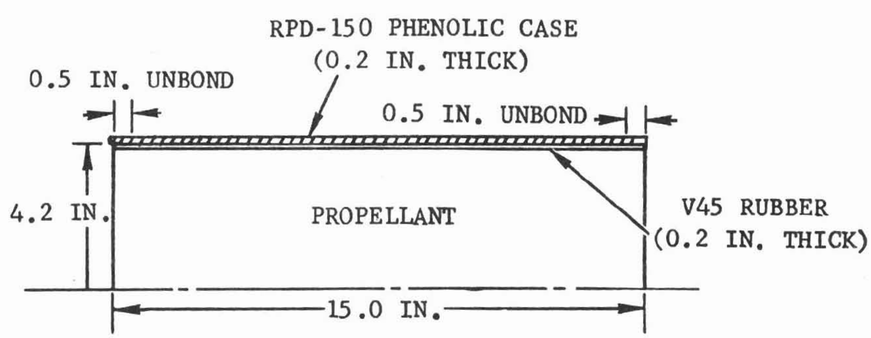


Figure 6-12b. Motor Analog for Case Bond Failure Due to Thermal Loading

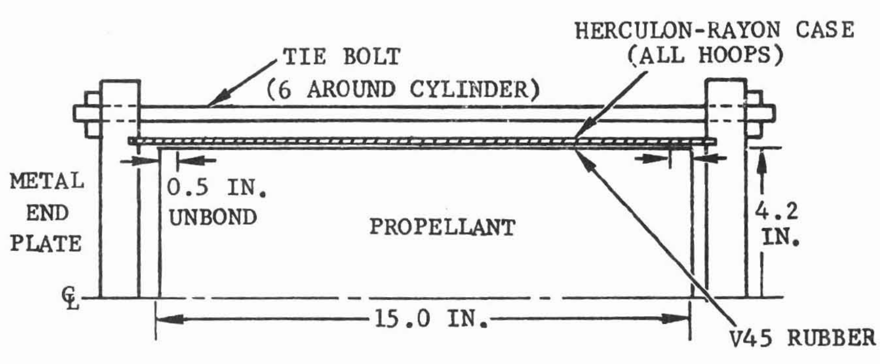


Figure 6-12c. Motor Analog for Case Bond Failure Due to Ignition

Figure 6-12. Motor Analogs

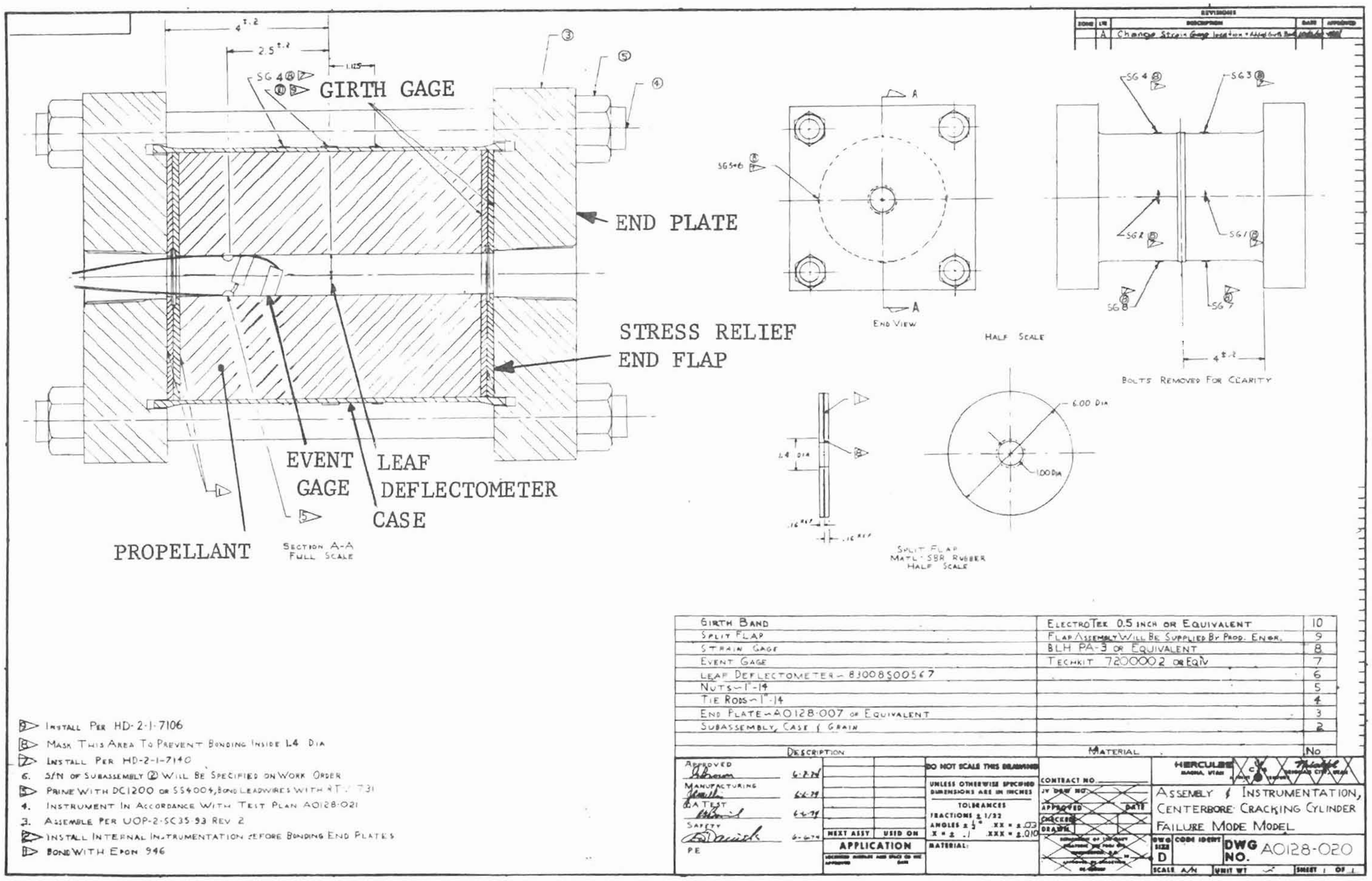


Figure 6-13. Circular Centerbore Model (Rubber Flap Design)

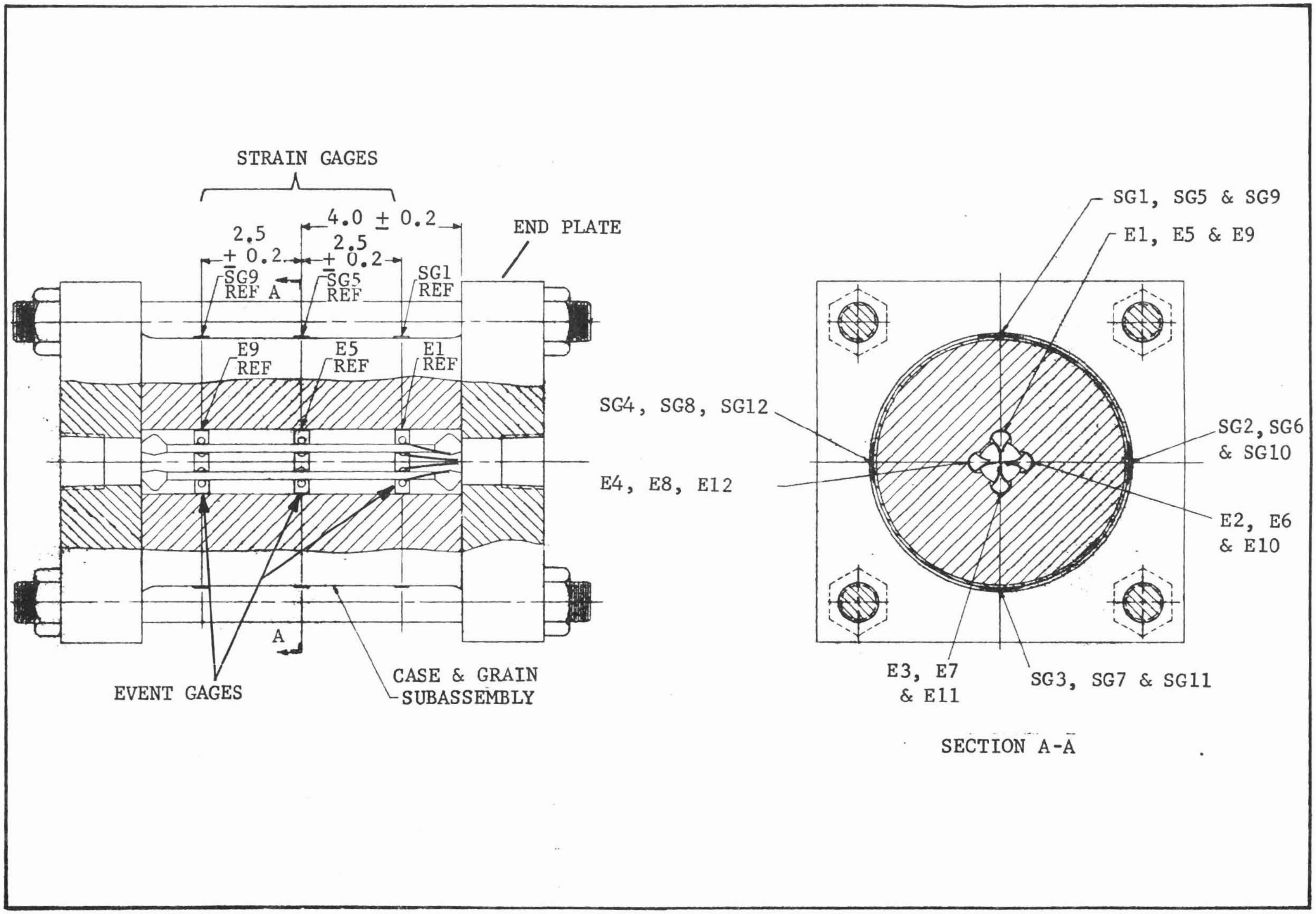


Figure 6-14. Wing Slot Cracking Failure Mode Slotted Model, Instrumented Assembly

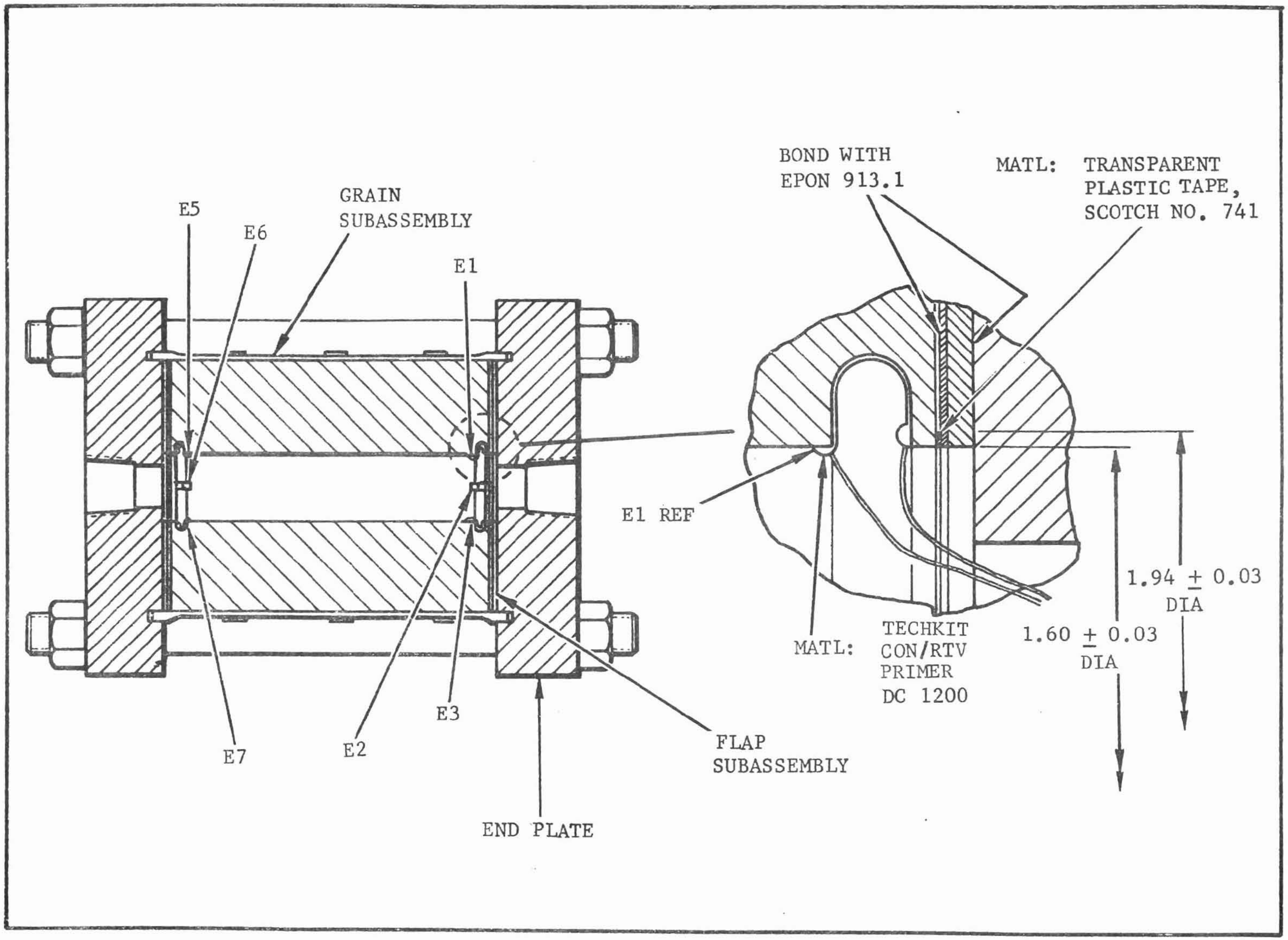


Figure 6-15. Instrumented Aft Center Port Failure Mode Model

Rigid end plates bonded to the grain and held together with rigid tie bolts is a method of producing plane-strain conditions. Many motors have bonded ends making the stress condition nearly that of plane strain; however, some axial strains are felt. Different end plate arrangements can be achieved which will allow varying amounts of axial strain in the subscales to reproduce the motor hoop-to-axial strain ratio. The design should be analyzed by state-of-the-art analysis methods and the centerport sized to achieve strains representative of the real motor.

A major problem is to keep the centerport large enough to allow installation of necessary instrumentation while making it small enough to produce desired strains thus permitting centerport cracking to take place before end plate debonding or other failure modes to occur. The smallest circular centerport diameter allowable from the instrumentation standpoint is approximately 1 inch.

Slotted grains result in higher surface strains and are more representative of some motors than the circular bore. The slotted grains should also be constrained to at least a 1-inch diameter centerbore and relatively wide shallow slots for instrumentation purposes. The slotted designs produce significantly higher strains than the circular centerport models, but they are more difficult to machine.

A bore surface cracking analog requires some type of stress relief to prevent end bonding. For propellants of moderate strength an end stress relief groove of the type shown in Figure 6-16 will suffice. For stronger propellants it may be necessary to resort to end flaps as was done in the ICBM Overtest Technology Program. Thus, it can be seen that this subscale unit can be used for evaluation of centerport cracking or centerport end termination debonding depending on the design at the end plates.

The following description applies to models used in the subject program. With some modification, it should apply to centerport failure mode analysis of other propellant types.

The model cases were filament-wound of Herculon/rayon (50/50) fiber and C7/W (50/50) resin, employing only hoop windings. After winding and cure the cases were machined to a wall thickness of 0.080 inch nominal, except for a 0.75-inch length at each end which was left thicker to fit the grooves in the end plates. Each case was pressure tested to determine its deformation-versus-pressure characteristics.

The propellant grains were machined from aged propellant, taken from a full-scale motor. In other programs the subscale units have been machined from slug castings. It should also be possible to cast directly into the subscale case. Each grain was machined to a slip fit into its assigned case. The centerbore and stress relief grooves were

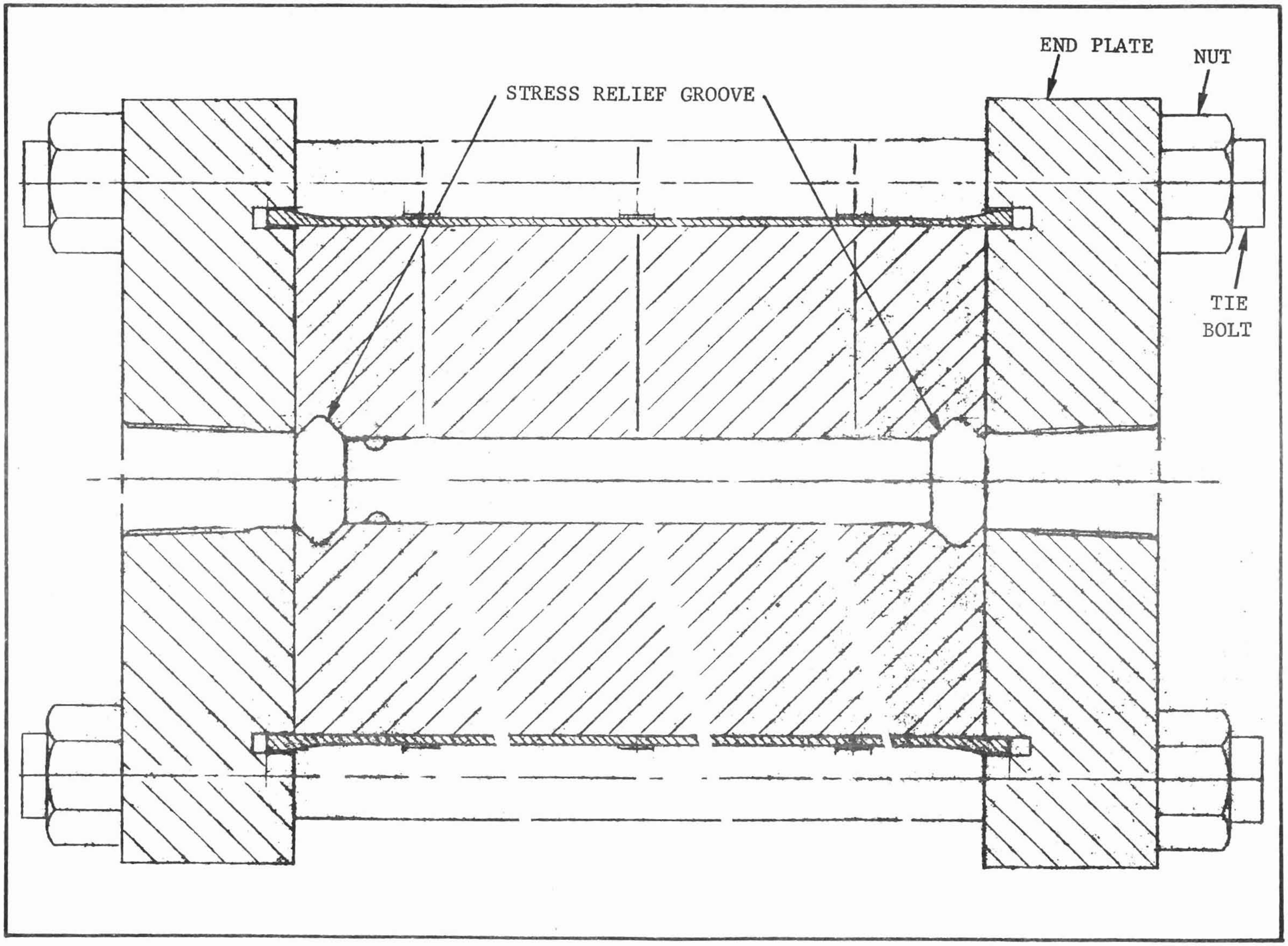


Figure 6-16. Stress Relief Groove in Motor Analog of Moderately Strong Propellant

machined in the circular bore model with conventional boring tools. To fabricate a slotted model, a circular bore was first machined and then the model was set up on a milling machine and a drill guide was inserted into the centerbore. A flat-pointed drill was then aligned by use of the drill guide, and one slot was drilled out from end-to-end of the grain. The grain was indexed 90^{o} and the second slot was drilled, and so forth. The grain was returned to the lathe, and a stress relief groove was cut in each end using a formed tool on a boring bar. Each grain was then bonded into its case with EA 913.1 adhesive and allowed to cure for 48 hours at ambient conditions.

Event gages were then installed in the grain centerbore. Circular bore models were equipped with one event gage inboard from the stress relief groove at each end of the grain. An event gage was installed at each end of the model and at the center of the model in each groove of the slotted models for a total of 12 gages in each slotted model.

End plates were bonded onto the model using EA 913.1 adhesive. The tie rods and nuts were installed and lightly tightened until the adhesive was observed squeezing out from between the end plate and the grain. The end plate bond was then cured for 48 hours at ambient conditions. The assembled instrumented models are shown in Figures 6-13 and 6-14.

2. Instrumentation of Analogs

Instrumentation is discussed in Paragraph H for both full-scale and subscale overtest units. Figure 6-13 shows instrumentation and locations for a typical subscale pressure overtest. The model was instrumented with 12 hoop strain gages. Internal event gages and centerbore deflectometers were provided for internal measurements. The leaf deflectometer assembly, consisting of two leaf deflectometers mounted on a rod with the centerbore and supported on bushings screwed into the end plates, is shown on Figure 6-17. Leadwires for the internal instrumentation were passed through the end plate and the high pressure piping, and finally out of the pressurized volume through a potted nipple. This leadwire system of necessity occupies part of the fluid piping volume and is exposed to the forces associated with the movement of the pressurizing fluid.

Due to the varied designs for partial motor analogs, no particular rules for instrumentation are offered. However, the partial motor analog articles are usually simple devices, and no special instrumentation beyond that to measure loads and deflections in a conventional test machine is required. In some instances it may be necessary to obtain more detailed strain resolution, in which case, optical methods may be employed. Following the movement of grid lines scribed on the test sample, visually or photographically, during the test is one way of getting strain measurements. A more precise method is the Moire fringe experimental strain analysis technique.[1]

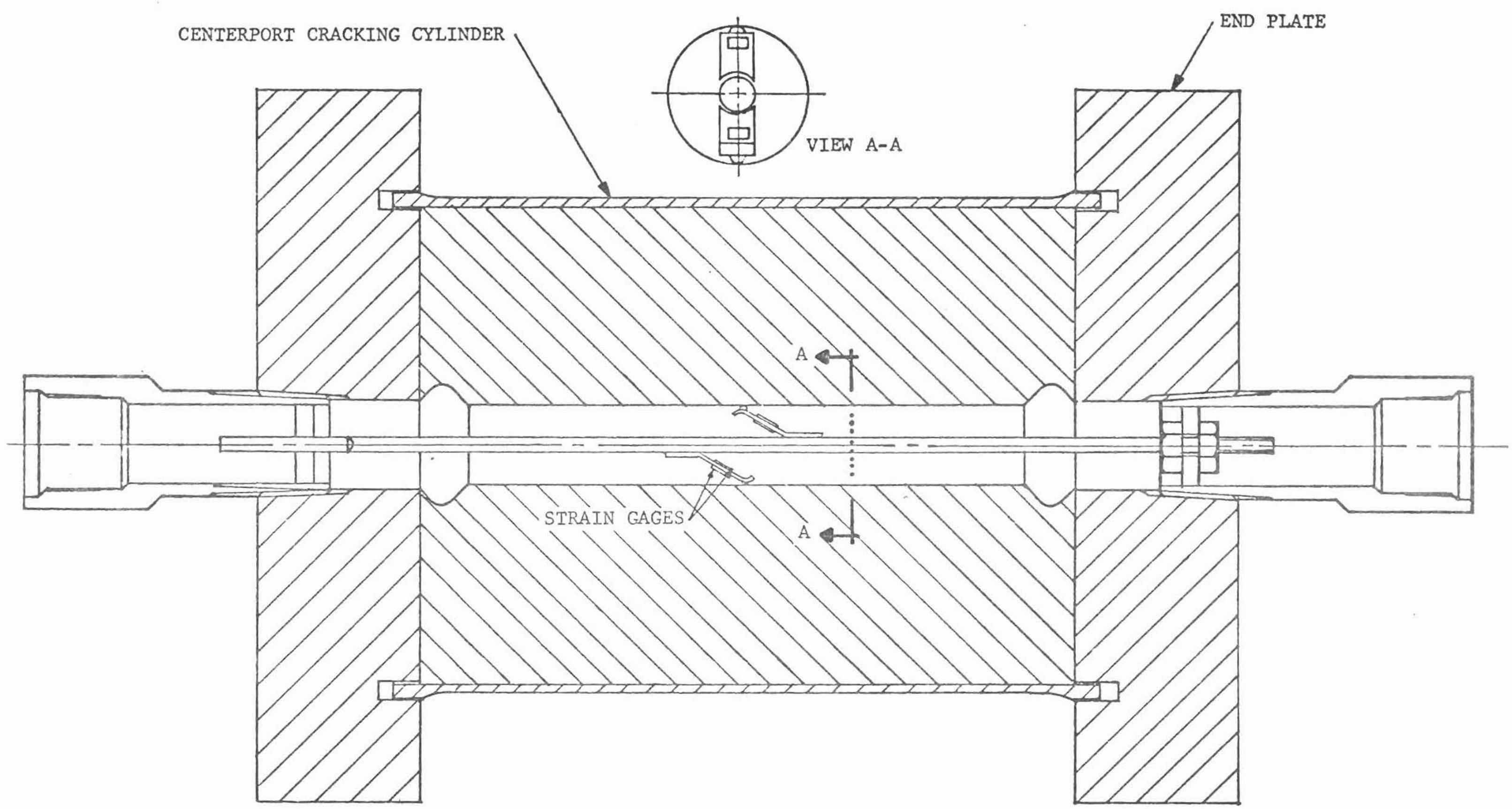


Figure 6-17. Leaf Deflectometer Assembly for Centerport Cracking Cylinder Test

3. Test Operations

The high-rate pressurization overtest was performed on subscale motor analogs to study grain cracking in the Minuteman II, stage III motor. Test procedures generated in that program are provided here as an aid in planning similar overtests relative to other motors. No attempt is made in this report to define methods applicable to other overtest approaches or types of loading which may be equally as useful in particular applications. The subscale unit tests on the ICBM overtest program are reported in Reference 6.

Figure 6-18 shows the assembled test arrangement for the ICBM overtest program subscale models, and Figure 6-19 gives a closer view of the model itself. This system is capable of applying test pressures up to 2500 psi at very high rates. The arrangement is comprised of a gas accumulator, high-rate valve, throttling valve, and high-pressure hose connected to both ends of the test model. In performing the high-rate test, the model and piping in front of the high-rate valve are filled with nonconductive mineral oil. The accumulator is charged with nitrogen gas. The high-rate valve separates the pressurized gas and the ambient-pressure oil until start of the test. As the high-rate valve is opened, it rapidly admits the pressurized gas, thus pressurizing the oil and model to the preset pressure determined by equilibrium of the total system volume.

This two-phase pressurization system incorporates many of the essential features of the motor high-rate hydrotest system. Testing of the model serves additionally as a small-scale checkout for the motor overtest system. Maximum test pressure is controlled by the pressure to which the accumulator is charged, and test pressurization rate is controlled by the throttle valve setting. The throttle valve settings are established by checkout runs in which a piece of pipe, having the same volume as the model centerbore cavity, is substituted for the model. However, if the pipe is much stiffer than the model, this must be accounted for or the checkout runs will give misleading results.

Standard procedures must be prepared and followed during preparation, testing, and inspection of subscale units. Appendix A includes procedures that are applicable to pressure testing of subscale partial-motor analogs. Additional details concerning test equipment and test setup are given in Reference 6, which is the technical report on the analog test phase of the ICBM Overtest Technology Program.

J. FULL-SCALE MOTOR TESTS

Full-scale motors are overtested to obtain information that cannot be confidently obtained otherwise. All questions regarding properties, analysis, failure criteria, etc, are eliminated in defining minimum structural capability of a particular motor by a successful overtest. As

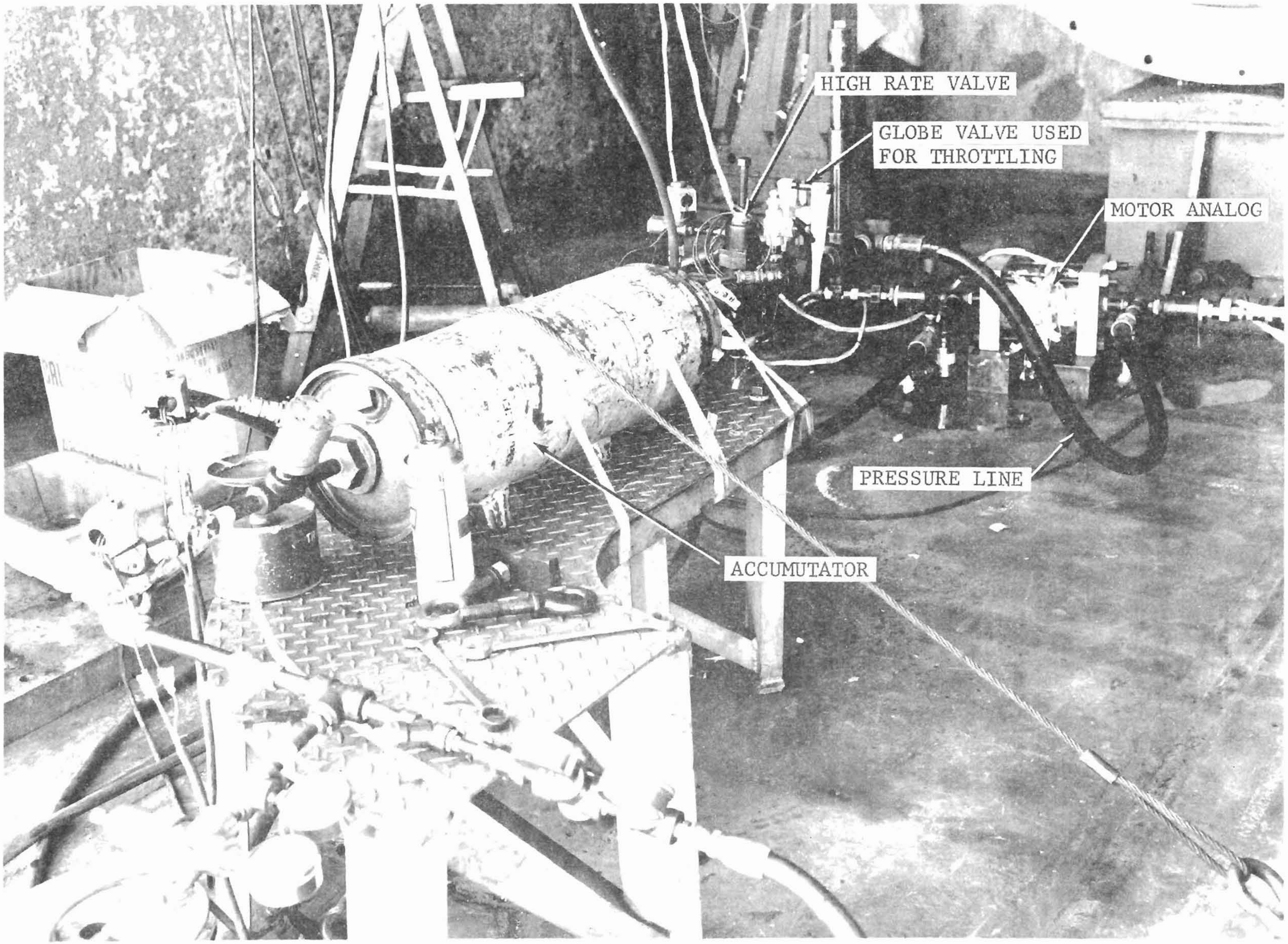


Figure 6-18. Overview of Model Test Arrangement

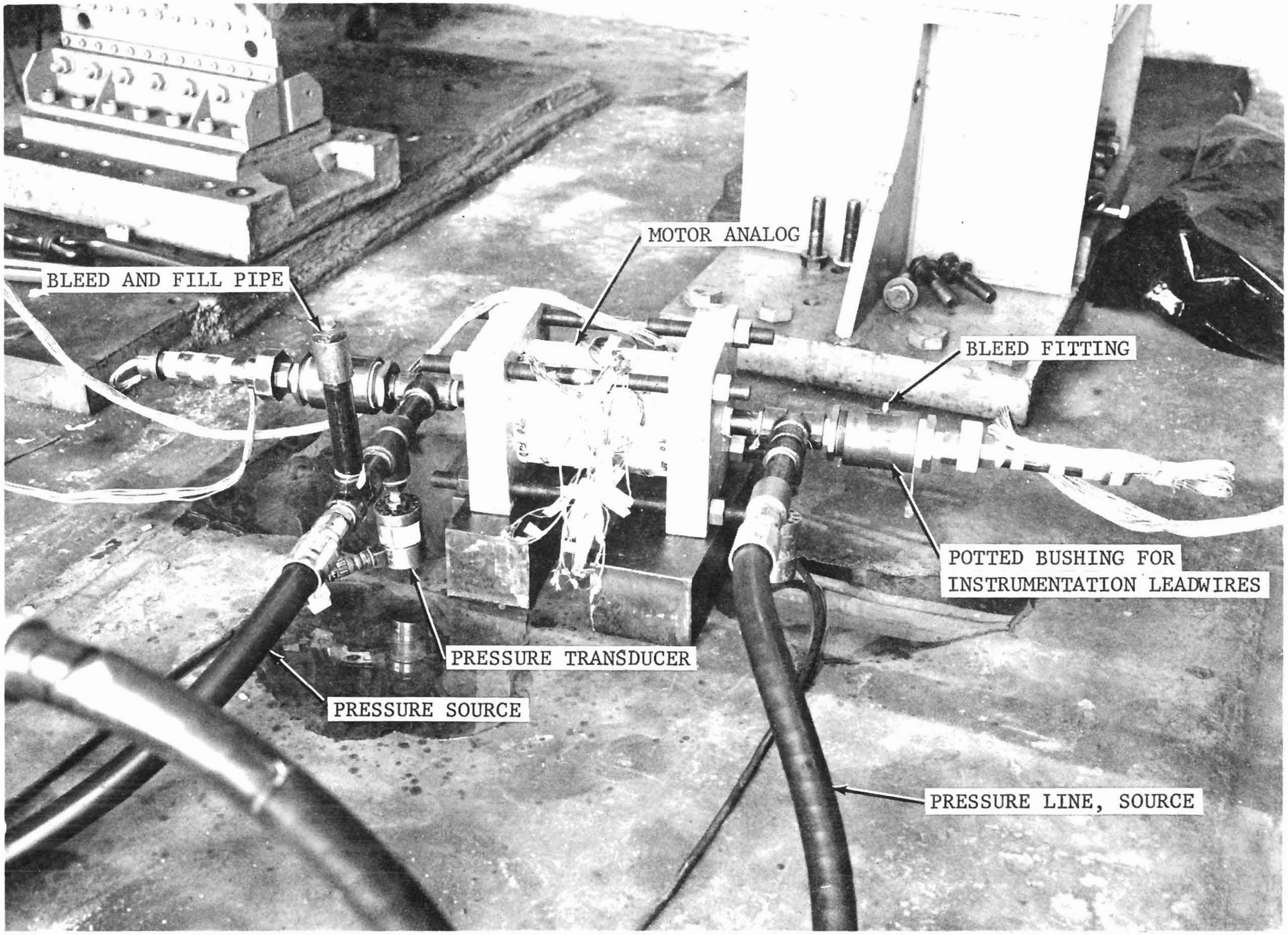


Figure 6-19. Subscale Model Installed in Test Arrangement

previously noted, the primary disadvantage of the full-scale test is its expense. Also, much planning and care is involved in achieving a successful and applicable overtest. Relating results from a few tests to a large motor population is a key problem of interpretation.

The major results to be obtained from full-scale motor overtests are: (1) Confirmation of critical failure modes, (2) verification of analysis, and (3) confirmation and/or understanding of analog devices. Results from an individual test contribute to the data to be used for structural reliability predictions, but due to the limited number performed, this is not sufficient justification for the test.

The principal elements of the full-scale overtest are:

(1) Motor selections

(2) Analysis

(3) Instrumentation

(4) Test planning and execution

(5) Inspection

These elements are presented, generally, in other paragraphs of this report, viz, D, E, F, and G. The intent in this paragraph is to relate them more specifically to the full-scale overtest program.

The full-scale overtest methodology in the ICBM overtest program was limited to motors that were available from field use. Consequently, the technology discussion in this section is limited. Also, the discussion is primarily directed to ignition-rate pressurization overtests. Although this is very probably a critical load, other critical loading conditions (Paragraph C) should be recognized also.

The following subparagraphs are devoted to considerations prior to the test, test instrumentation, and test performance. These subparagraphs should be considered along with other major paragraphs of this report in defining an overtest program.

1. <u>Preliminary Considerations</u>

The full-scale motor overtest is basic to the concept of overtest technology applicable to a predictive surveillance program. By the full-scale overtest, confidence is established for the more economical analytical and subscale analog tasks which are also necessary ingredients of the overtest program. Specific objectives of the full-scale overtest are presented in Paragraph C.

Unlike the analog articles, the full-scale design is predetermined in that it must be representative of the actual motor design. For operational motors, the overtest sample is removed directly from the operational force. For motors in development or production, they can be assigned specifically to the overtest program. In some rate instances, motors have been planned as structural vehicles prior to their manufacture; consequently, it was possible to incorporate special instrumentation useful for overtest purposes.

There is a great desire in a large motor program to use line-loss motors in aging and surveillance programs. This philosophy is expected to prevail in expanding the use of overtest technology. Fundamentally, there is nothing wrong with using motors that have been rejected for field use if the reason for rejecting them does not affect the failure mode under investigation. This point requires careful consideration in choosing a motor which may perhaps influence the conduct of a long-duration predictive surveillance program.

Another consideration in the use of line-loss motors is that they may not represent particular lots or motor subsets where such differences are important. Differences that should be considered important are primarily those that may result in a change in the order of failure mode criticality.

In summary, full-scale motors used in the overtest program must be representative of the design and manufacturing procedures of the motor population under investigation.

Ideally, a full-scale unit should be tested for each critical failure mode. However, failure by one mode (the most critical) is likely to alter the results pertaining to other modes. If more than one critical failure mode is identified and their margins of safety indicate similar failure levels, possibilities of failure by either mode should be recognized in the program planning.

Detailed structural analyses should be performed on specific motors to be overtested. Properties for use in the analysis should be obtained by sectioning and testing of propellant from low-strain regions of the motor and/or applicable propellant samples taken at the time of manufacture. Case growth behavior under pressure should be defined for the particular motor case. This is usually standard procedure associated with hydroproof prior to use. However, instrumentation in addition to normal hydroproof instrumentation may be required. Other loads should be predicted for each of the critical failure modes and the exact loading program imposed on the test motor. It is necessary to define (to the extent possible with the present state of analysis knowledge) the predictive structural performance of the specific motor during the overtest. These results can then be correlated with the overtest results to establish relationships between full-scale experiment and analysis. Results from the analog tests performed on propellant representative of the overtest motor are similarly correlated with the full-scale results to define full-scale motor-to-analog relations. The subject of analysis is addressed in Paragraph G of this report.

2. Instrumentation of Full-Scale Overtest Motors

A general discussion of instrumentation applicable to high-rate pressurization overtests was presented in Paragraph H and, therefore, will not be repeated here. It cannot be overemphasized, however, that instrumentation should be planned to identify as precisely as possible the exact load and location at which failure is initiated in a given overtest. Particularly for full-scale motors, the failure loads must be defined with a minimum of tests. In principle, it should be possible to test to various loads and examine the motor afterward, to determine which loads did and did not cause failure. By progressively increasing the load, or by bracketing, the failure level is determined by examination, and failure detection during the test is not a problem. However, the expense of such a program is prohibitive with ICBM motors.

The Minuteman, stage III is used to typify instrumentation of a full-scale ICBM motor. Modifications to this plan will be necessary based on the motor design and critical failure modes.

The motor external instrumentation locations are shown in Figure 6-20. Eight strain gages were installed on the cylindrical section of the case, directly outboard of the critical slot tip cross-section (in line with the expected failure site). The case strain gages were oriented in the hoop direction. Eight strain gages were installed on the aft dome; these gages were located on four 45° azimuths and oriented in the hoop direction. All 16 strain gages were intended to respond to grain cracking or centerport debonding and to measure case strain during motor pressurization. Propellant cracking or port debonding results in a rapid transfer of test pressure load from the grain to the case or dome. Hence, a sudden shift in measured case strain is an indication that a structural failure has occurred. The degree to which the gages respond to such a transfer of load depends upon the propellant properties and how much load is carried by the grain when it fractures.

Pressure transducers were installed in nozzle ports 1, 2, and 4 and in the aft centerport. In previous high rate hydrotests, pressure data showed a high frequency oscillation, which was believed to originate in the instrumentation, not in the motor. To avoid this oscillation, extra precautions were taken with the transducer installation. First, the tubing lengths which connected the port closure and the transducer was made as short as possible. Second, the transducers were filled with oil and subjected to vacuum to boil out all the air trapped in the transducer. Finally, to ensure that the transducer tubing would be free of air, the transducers were installed after the motor had been filled with mineral oil; oil was allowed to flow out of the tubing during transducer hookup to prevent entrapping of air bubbles.

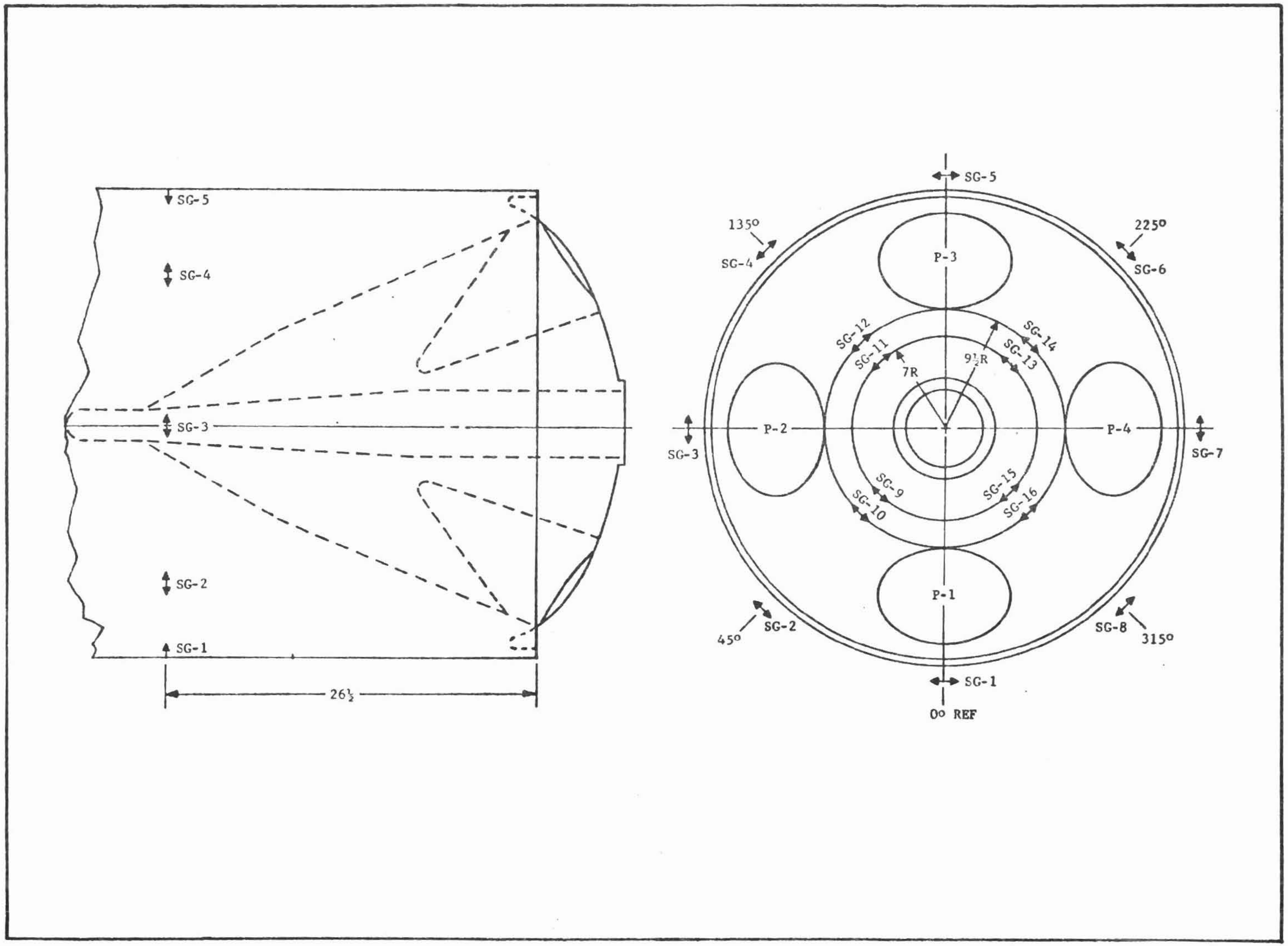


Figure 6-20. External Strain Gage Locations

Figure 6-21 shows the locations of the instrumentation installed in the propellant grain cavity. A total of 44 instruments was specified. Linear potentiometers were installed in three wing slots to measure the change in slot width.

Five event gages were installed in each wing slot. The forward-most row (E1 through E4) was near the slot-centerbore intersection and was thus applied over one of the expected areas of maximum stress concentration in the Minuteman motor. The second row (E5 through E8) was at a slot tip critical cross section (3.7-inch radius). The third, fourth, and fifth rows were located 10-1/8, 16-3/4, and 23 inches, respectively, from the forward end of the slots. Two event gages were installed over the boot-flap bonded interface in the aft centerport, and two were installed in the stress relief groove.

Two linear potentiometers were installed in the forward center core; one oriented on the 0° to 180° azimuth and one at 90° to 270°. The potentiometer was mounted on a bracket which in turn was bonded to the propellant surface. Two linear potentiometers with bracketry were installed in the aft end of the center core; oriented at 0° to 180° and 90° to 270°. One linear potentiometer was installed on a diameter across the stress relief groove. Two linear potentiometers were each bonded to the surface of the aft center core just forward of the stress relief groove. These potentiometers measured the relative displacement of plates bonded to the inside diameter of the aft center core just aft of the boot-flap bond. Thus, these potentiometers were expected to respond to debonding by recording an abrupt extension of the potentiometer. The specific instrumentation arrangements are presented in detail in Reference 6.

3. Test Operations

The overtest operations for full-scale Minuteman II, stage III motors are described in Reference 6. Test procedures generated in that program and previous programs are summarized here as an aid in planning other high-rate-pressure overtest programs. Reference 6 provides a more complete explanation of the tests.

A drawing of a high-rate pressurization system is given in Figure 6-22. The system shown is for a four-nozzle motor, but arrangements for single-nozzle motors will generally be the same. Components for the system must be sized in accordance with local plant policies and the particular motor load requirements. Therefore, it is not possible to specify a test arrangement that is universally applicable. This presentation is intended to serve as a guideline only in the design of a pressure overtest system.

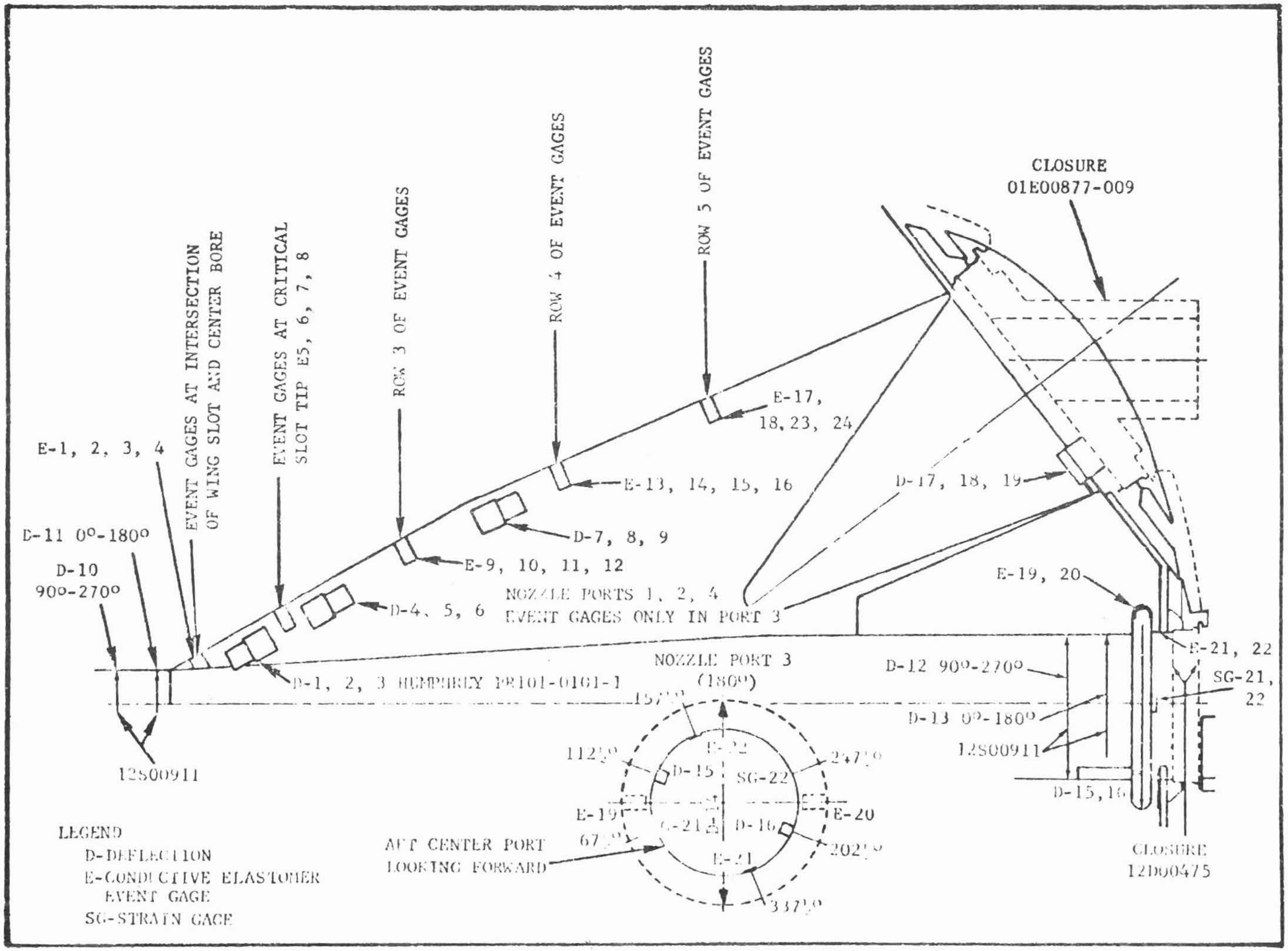


Figure 6-21. Grain Instrumentation Locations

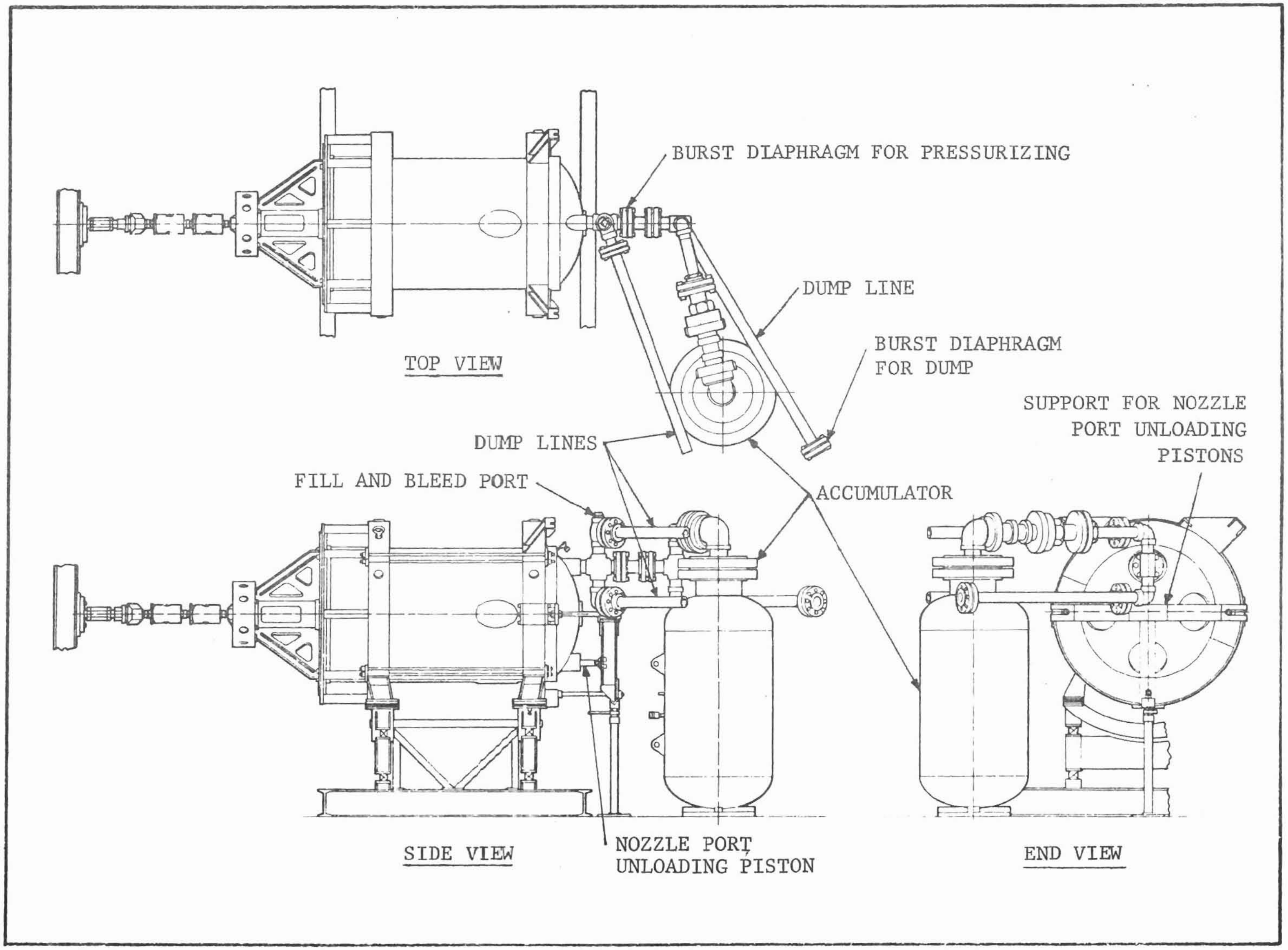


Figure 6-22. High Rate Pressurization System

Major components of the system, in addition to the motor, are: Accumulator, burst diaphragms, high pressure feed and dump lines, and in the case of four-nozzle motors, nozzle, and unloading pistons. Hercules recommends nonconductive mineral oil (discussed below) as the pressurization medium in contact with the propellant grain.

Operation of the system is as follows: The motor grain cavity and the part of the piping system on the motor side of the pressurizing burst diaphragm is initially filled with mineral oil. Nitrogen gas is stored at a predetermined pressure, dependent upon motor volume and deflection characteristics, in the accumulator. The high-rate pressurization of the motor is accomplished by blowing the rupture diaphragm with a flexible linear shaped charge (FLSC). As the diaphragm is ruptured the nitrogen pressure is applied to the oil, and the entire system comes to pressure equilibrium. The pressure rate is limited through the use of a sharp-edged orifice in the gas line between the accumulator and the motor. The rating of the rupture diaphragm and sizing of the orifice must be related to the particular test requirement, and the system operation should be confirmed prior to the test program.

In some situations it will be desired to hold the pressure on the motor for a chosen period of time. The arrangement in Figure 6-22 allows for this possibility by the use of dump lines. Rapid relief is achieved by bursting a diaphragm in much the same way as is done to pressurize the motor.

A pretest photograph of the motor and test arrangement is given in Figure 6-23. The motor was mounted in a modified firing harness and installed in the horizontal position on a firing stand. The firing harness was attached to a firing pylon, but no thrust gage was installed. Nozzle ports were positioned at the same locations as in a static firing. Nozzle port No. 3 was closed with an adapter to which a 3-inch pipe, running from the nitrogen pressure vessel, was attached. The other three ports were closed with hydrotest closures. Hydrotest closures each incorporate an unloading piston, of the same diameter as the nozzle throat, which is supported by a cross framework and tie bolts attached to the aft harness ring. The unloading pistons simulate the unloading effect of the motor nozzle in reducing the total pressure load on the aft dome. The igniter port was sealed with a solid closure. The closures were pierced, as necessary, to admit instrumentation cables to the motor and to attach pressure transducer piping.

The test arrangement also included a depressurization system. The motor was vented through three 3-inch lines, two of which were connected to the pressure piping immediately adjacent to nozzle port No. 3, and one which was connected to the piping between the pressure vessel and the burst diaphragm. Each vent line was sealed with a 1250 psi burst diaphragm, equipped with a FLSC. The vent charges were fired by a pressure-actuated switch, set to operate at 540 psi, the desired pressure level.

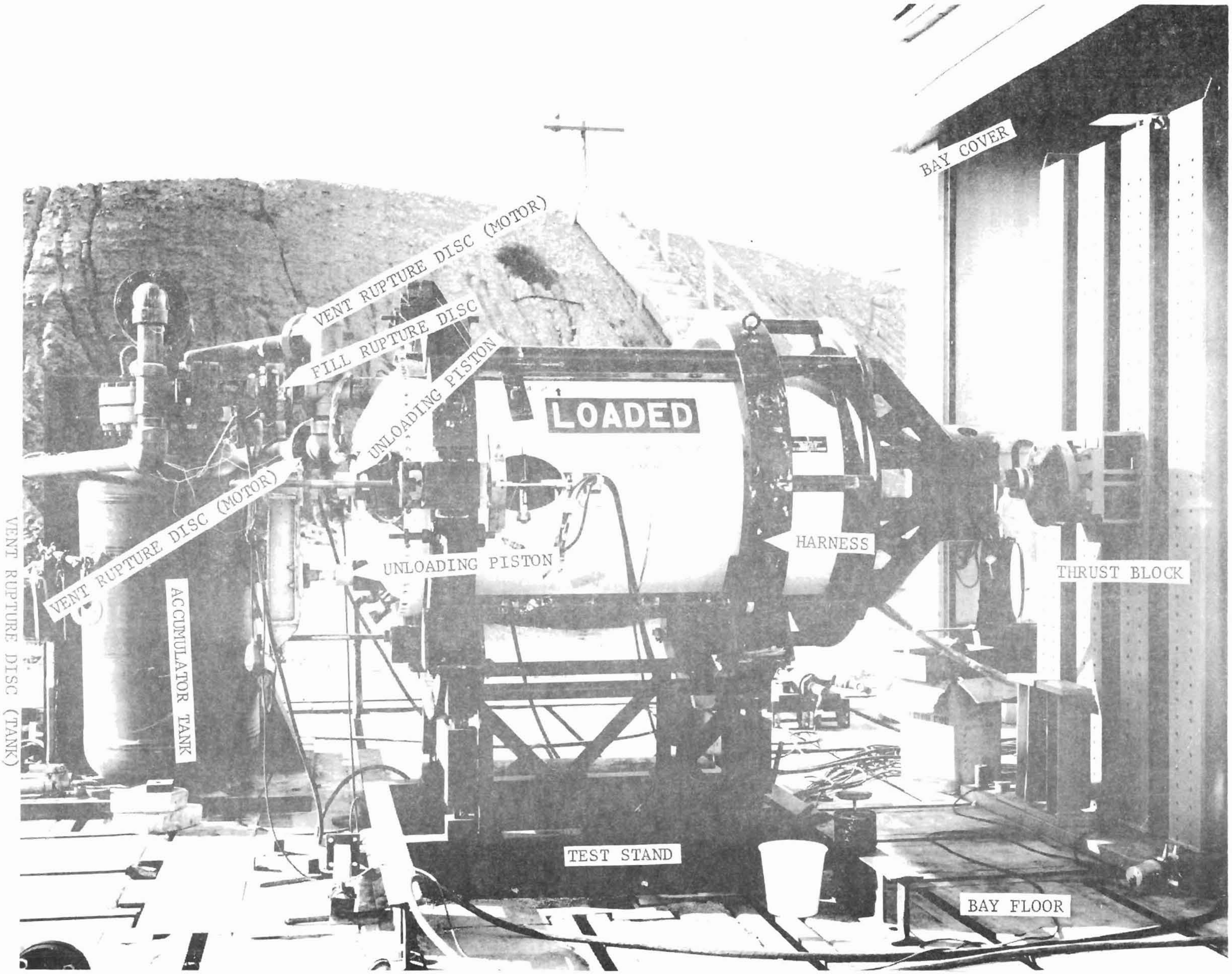


Figure 6-23. Test Setup Motor 0032765

The choice of a nonconductive oil as the pressurization fluid needs some explanation. A liquid, such as mineral oil, is preferred in direct contact with the propellant instead of gas. Safety considerations predominate in this preference for a liquid. This is particularly significant if a burst diaphragm is used to admit pressure to the motor. As the diaphragm bursts, small metal particles are torn from the diaphragm even if it is scribed to cause failure along predetermined lines. A liquid slows down and cools the particles more than does a gas, thus minimizing the impact energy and the possibility of inadvertent ignition of the motor. Use of a liquid is especially indicated when a pyrotechnic device is used to break the burst diaphragm. Small fires have been experienced in using the pyrotechnic devices in this way.

The second safety feature that favors the use of a liquid concerns the possibility that high-rate testing will proceed beyond the desired limits and split the motor case. By using a liquid in the grain cavity, the required accumulator pressure and volume are minimized, thus simplifying the system design. Minimizing the accumulator pressure and volume also minimizes the stored energy and will thus reduce the possibility of damage by chamber rupture and/or other accidental sudden release of the work stored in the gas.

In special situations in which gas is safe to use alone as the pressurizing medium, it does offer two significant advantages. First, since gas is much less dense than liquid, the impact forces against the instrumentation and wiring will be lower and less likely to tear instrumentation out of position. Second, unprotected elastomeric event gages may be penetrated by liquids and rendered nonconductive, whereas gas will have no such effect.

The primary consideration in selecting a liquid to be used in high-rate testing is that it be nonconductive. Instrumentation, such as linear potentiometers, would be immediately shorted out if exposed to a conductive fluid, such as water. Although event gages and elastomeric strain gages could perhaps be protected by the same technique as used to waterproof wire strain gages, these techniques have not been proven for use on a substrate capable of high elongation, such as propellant.

Five motors were successfully high rate tested by Hercules from 1963 through 1965 using nonconductive mineral oil. The suitability of mineral oil was further demonstrated by additional characterization in the LRSLA and overtest programs. Compatibility with propellant was checked, and it was found that the oil did not chemically react with propellant. The absorption of nitroglycerin from propellant into mineral oil was found to be less than one part per thousand in 24 hours. This was judged to be a safe level for high-rate testing but also indicated that used mineral oil should be disposed of in accordance with procedures for contaminated materials.

Tensile test samples that were soaked in oil were tested to determine the effect of oil immersion on propellant strain capability. Oil immersion was found to slightly lower the failure properties of CYH propellant, but the effect was so small that motor failure predictions would not be distorted.

A test plan outlining the test and related operations should be prepared for each overtest operation. Any deviations to the prescribed plan should be noted in a log of the motor history. A typical test plan is outlined in Appendix B.

LIST OF REFERENCES

1. JANNAF Solid Propellant Structural Integrity Handbook, SMBWG, Structural Integrity Committee, S. C. Browning, Chairman, CPIA Publication 230; UTEC CE 72-160, September 1972.

2. Case Bond Stress Calculations for Flapped Cylindrical Analogs of Solid Propellant Rocket Motors, Bondline Parametric Studies, Task I, Interim Technical Report, AFRPL-TR-72-77, Hercules Incorporated, Magna, Utah, May 1972.

3. L. D. Webb, R. W. Harris, E. T. Cook, Study and Literature Survey of Stress State Transducer Development, Final Report, Volume II, Bibliography, Texas A & M University, AFRPL-TR-69-74, Volume II, R-4532-11, March 1969.

4. H. Leeming, Techniques for Measuring Stress, Strain and Temperature in Solid Propellant Motors, Lockheed Propulsion Company, Redlands, Calif, AFRPL-TR-71-131, November 1971.

5. L. D. Webb, "Development of an In Situ Transmitter for Solid Rocket Propellant Surveillance," Task I, Feasibility Study, Part II, Literature Survey on Instrumentation and Measurement Techniques, Texas A & M University, Report No. 1 & 26-26F, November 1972.

6. A. S. Daniels, ICBM Overtest Technology, Motor Overtest (Task IV) and Posttest Examination, Hercules Incorporated, Magna, Utah, Report No. AFRPL-TR-(in review), February 1975.

7. "Strain Gage Comes Through in the Stretch," Machine Design, 12 July 1973.

8. Edward E. Herceg, Handbook of Measurement and Control, Schaevitz Engineering, Pennsauken, Pa, 1972.

9. J. M. Anderson, T. D. Pavelka, and P. S. Bruno, Techniques for Assessing Case Liner-Bond Integrity in Solid Propellant Rocket Motors, Hercules Incorporated, Magna, Utah, AFRPL-TR-73-75, September 1973.

10. S. R. Swanson, Subscale Motor Verification Program, Report No. -544/6/40-168, Hercules Incorporated, Magna, Utah, 10 February 1967.

APPENDIX A

SPECIFIC TEST PLAN

FOR

PRESSURIZATION TESTING OF

SUBSCALE CENTERBORE CRACKING CYLINDER

FAILURE MODE MODEL

FOR

THE RPL ICBM OVERTEST

TECHNOLOGY PROGRAM

I. INTRODUCTION

This test plan describes the requirements and procedures applicable to the High Rate Hydrotest of a Centerbore Cracking Cylinder Failure Mode Subscale Model.

Any change to this test plan is to be documented on a QA Testing Event Record (Form BW-6000/769) and approved by QA Test Engineering, Product Engineering and Test Area Supervision.

II. TEST OBJECTIVES

(a) To verify that the high rate hydrotest is a valid overtest for the wing-slot-cracking failure mode.

(b) To measure the pressure/strain at which centerbore cracking occurs in the circular centerbore model.

III. TEST ITEM DESCRIPTION

The centerbore cracking cylinder failure mode model is as shown in Figure A-1. It is a machined grain of CYH propellant bonded into a hoop-wound case of Herculon-nylon fiber and C7/W resin. The grain is 6 inches OD by 1 inch ID by 7.35 inches long. A flap subassembly is bonded to each end of the grain. The flap subassembly is made of two each 0.16-inch SBR silica filled rubber pieces bonded together. The ends of the motor are sealed with aluminum end plates bonded to the flap subassembly and axially restrained by four each tie rods bolted between the end plates.

The model is internally instrumented with two leaf deflectometers and a conductive RTV event gage. The model is externally instrumented with eight case-mounted strain gages and one girth band.

IV. TEST LOADS, ENVIRONMENTS, AND CONDITIONS

(a) The motor will be maintained and the test conducted at a temperature of $70^{\circ} \pm 2^{\circ}$ F.

(b) The centerbore cracking cylinder failure mode model will be pressurized to 1250 psi at a rate of 10,000 psi/sec using mineral oil as the cavity pressurizing fluid.

(c) The mineral oil will be maintained at a temperature of $70^{\circ} \pm 2^{\circ}$ F.

(d) The test will be conducted at the Plant 1 Range Facility.

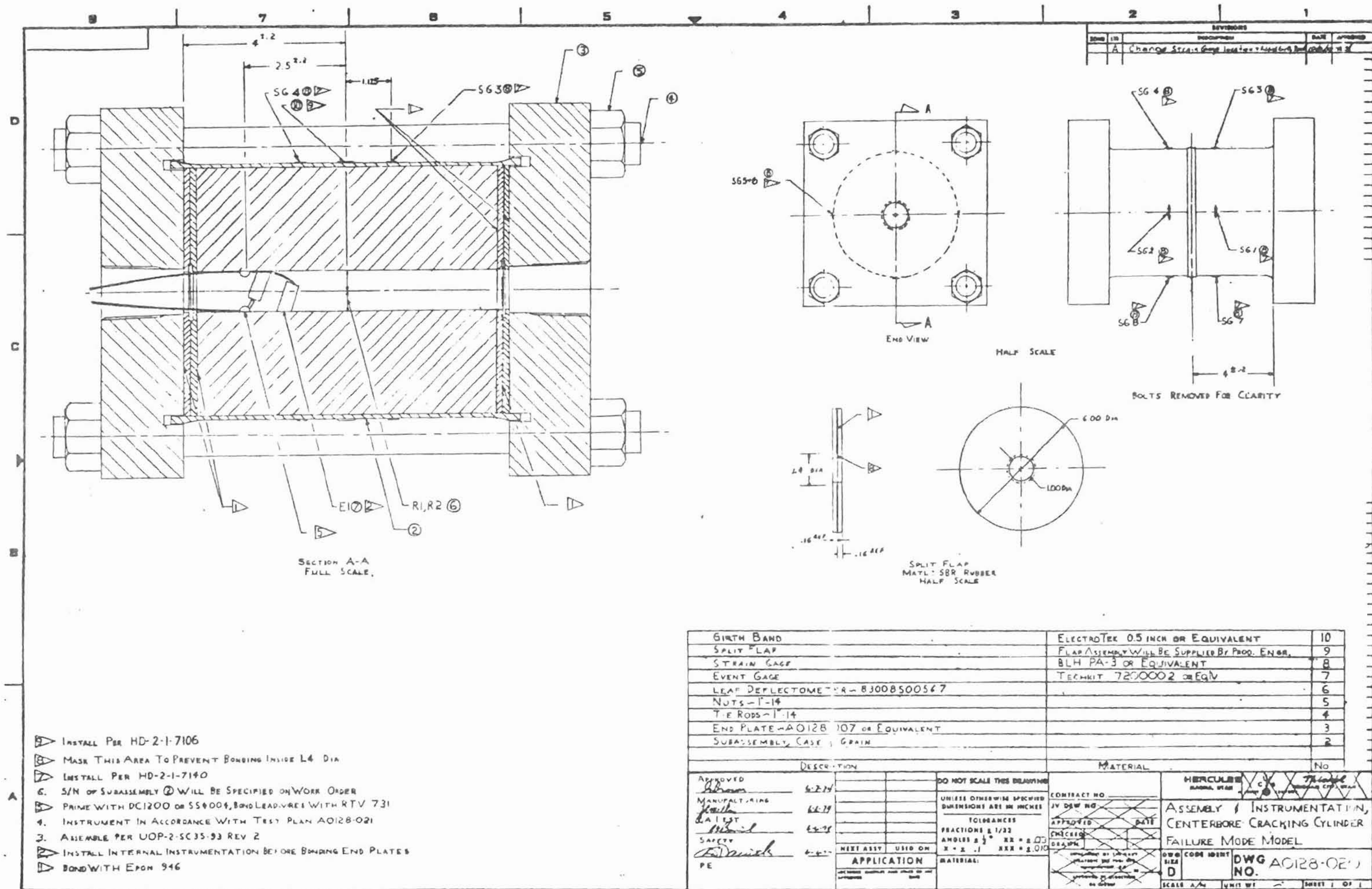


Figure A-1. Cracking Cylinder Failure Mode Model

V. TEST PROCEDURE

(a) Instrument the motor and associated test equipment with strain grids, girth band, leaf deflectometers, and pressure transducers in accordance with the Data Acquisition Instruction. (See Table A-1.)

(b) Assemble the pressurization system in accordance with Figure A-2 and as directed per HD 2-1-3127 (Subscale Pressurization Tests). The system must be capable of handling a minimum expected pressure of 1250 psi at a maximum rate of 10,000 psi/sec.

(c) Install the test cylinder and remaining instrumentation in accordance with Data Acquisition Instruction. (See Table A-1 and Figure A-1.)

(d) Pressurize the test cylinder per HD-2-1-3127 to 1250 psig at a rate of 10,000 psi/sec.

VI. DATA REQUIREMENTS

A. Instrumentation

The motor/test fixtures will be instrumented and the data will be recorded in accordance with the Data Acquisition Instruction. (See Table A-1.) Two leaf deflectometers are mounted at 180° on a 1/4-inch rod held coaxial to the model centerline. Each deflectometer measures the radial displacement of the centerbore wall. The sum of both radial deflections is the diametrical deflection of the centerbore, as the extraneous motions of the support rod cancel out. One end of the support rod passes through a flat-sided hole in one support bushing so it is free to slide axially, but prevented from rotating. The other end of the rod passes through a hole in the other support bushing and is clamped to it by a nut. The flow area through support bushings is reduced by 35 percent by the plates which support the rod. The deflectometers are to be compressed during installation enough to get past the event gages and to keep from dragging on the propellant until they are in place.

B. Data Reduction

Engineering unit line plots of all data channels at 1 ms sampling rate for the first 1000 ms are required.

Additional information will be reduced as requested by the Product Engineering project engineer.

DATA ACQUISITION INSTRUCTIONS - TABLE A-1

BW-6000 435 (9-63)

CODES:

FM - Frequency Modulation (in./sec magnetic tape speed)
RO - Recording Oscillograph (in./sec)

I/C - Iron Constantan
C/A - Chromel/Alumel
P/P10%R - Platinum/Platinum 10% Rhodium
MV - Millivolts

MEASUREMENT PRIORITIES

1. Hold test until instrument is operative.
2. These measurements may be deleted only upon direction of the cognizant HPC test conductor.

TEST NO.

SHEET 1 OF 1

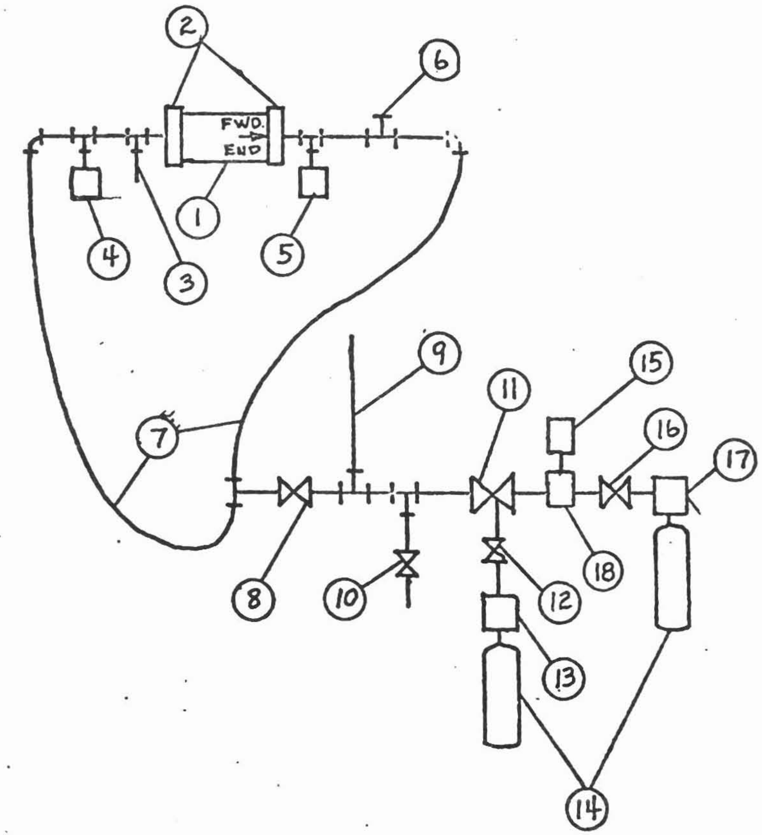
MOTOR INSTRUMENT LIST S N: M 1- 17SD006

APPROVED BY

MEASUREMENT NUMBER	TYPE: MEASUREMENT	TYPE: TRANSDUCER	LOCATION AND/OR INSTALLATION DRAWING	PRIORITY	PURPOSE OF MEASUREMENT	EXPECTED RANGE	RECORDING MODES		
*P-1 *P-2	Pressure	Taber 2000 psig or Equivalent	Figure 2	1	Chamber Pressure	1500 psig	D-250	FM-60	RO-16
P-3	Pressure	Taber 2000 psig or Equivalent	Figure 2	1	Nitrogen Pressure	2000 psig	D-250	FM-60	RO-16
R1 R2	Deflection		Figure 1	1	Change in Center Diameter	0.5 Inch	D-250	FM-60	RO-16
SG-1 Through SG-8	Strain	BLH PA-3 or Equiv.	AO 128-020 Figure 1	2	Circumferential Growth	± 3%	D-250	FM-60	RO-16
*T-1 (Time "0")	Valve	Breakwire					D-250	FM-60	RO-16
E-1	Event	Conductive RTV Gage	Figure 1	1	Time of Centerbore Cracking	2 Ω to 1 meg Ω	D-250	FM-60	RO-16
D-1	Deflection	ElectroTek .25 Inch or Equiv.	Figure 2	2	Circumferential Growth	.5 Inch	D-250	FM-60	RO-16

*P-1, P-2 and T-1 should be recorded on all FM tapes and visicorders.

Item No.	Description	Function
1	Subscale Motor	Test Item
2	Aluminum End Plates	Hold Motor
3	Potted Nipple	Instrumentation Leadwire Exit
4	Taber Pressure Gage	Chamber Pressure P-1
5	Taber Pressure Gage	Chamber Pressure P-2
6	Tee & Plug	Bleed Hole
7	Flexible Hose	Piping
8	Needle Valve	Regulate Pressurization Rate
9	Oil Fill Pipe & Plug	Fill System with Oil
10	ASCO Solenoid	Exhaust & Drain System
11	Pneumatic Valve	Pressurize Motor
12	ASCO Solenoid	Initiate Pneumatic Valve Remotely
13	Pressure Regulator	Control Pressure to Pneumatic Valve
14	Nitrogen Tank	Supply Driving Pressure
15	Taber Pressure Gage	Driving Pressure P-3
16	ASCO Solenoid	Control Driving Pressure Remotely
17	Pressure Regulator	Regulate Driving Pressure
18	Pressure Vessel	Provide Driving Force



Brief Description of Operation

The system is filled with mineral oil on the motor side of valve 11. This is done by filling at 9 and bleeding at 6. Pressure vessel 18 is then pressurized with nitrogen to the desired driving pressure by actuating valve 16 remotely and monitoring the pressure rise on 15. When 18 reaches the pressure desired, 16 is closed and motor pressurization is accomplished by actuating the rapid opening valve, 11. The system is then exhausted by opening valve 10.

Figure A-2. Subscale Pressurization System

VII. PHOTOGRAPHIC COVERAGE

Black and white still photographs of the motor/test arrangement are required.

The quantity and views of photographs to be taken shall be at the discretion of the Test Engineer.

APPENDIX B

SPECIFIC TEST PLAN

FOR

HIGH RATE HYDROTEST OF M57-A1 MOTOR

S/N 0033348

FOR

THE RPL ICBM OVERTEST TECHNOLOGY PROGRAM

I. INTRODUCTION

These requirements outline the high-rate hydrotest of a 6-year old M57A1 rocket motor, which comprises a portion of Task IV of the ICBM Overtest Technology Program. The objective of the program is to establish and verify methodology for structural overtest to be used for service life assessment of solid fuel rocket motors. A secondary objective is to determine the current margin of safety for the M57A1 motor.

This will be the second, and last, high-rate motor hydrotest performed for the ICBM Overtest Technology Program. A discussion of the program background was given in the Test Plan describing the first motor test (Report No. A0128-016). The second hydrotest is to be conducted like the first test so as to produce comparable data for both motors. Some differences in test operations and instrumentation will be required because of the design differences between the two motors. The same hydrotest arrangement will be used in an attempt to duplicate the pressure rates of the first test.

Instrumentation locations specified for this test also duplicate those used in the first test. Some changes have been made, either because the test pressure is higher or to accommodate the design differences that exist between the first and second test motors. Higher pressures imply higher grain deflections, so wing slot potentiometer assemblies capable of sufficient stroke are specified herein, where space permits mounting them. These pot assemblies are capable of recording reliable data only while the wing slot width is increasing; so assembly has demonstrated a tendency to buckle during pressure blowdown when the wing slot relaxes. Failure of the vulcanized aft center port bond of this test motor configuration is not considered a potential failure mode. Hence, this area requires less instrumentation than was used on the preceding test. Four event gages are located to detect cracking in the aft end web; extensive cracking occurred in this area in the previous test.

II. TEST DESCRIPTION

A. Test Item

Third stage Minuteman II motor S/N 0033348 has been selected as the second motor to be subjected to overtest in the ICBM overtest program. The motor configuration is in accordance with 01A00063-027, and includes the OPRI design changes. The grain was made from CYH propellant powder lot number RAD 1-16-67, which exhibited a modulus at acceptance of 802 psi and tensile strength of 295 psi. The motor case is from production lot number 44B, which demonstrated a minimum hydroburst pressure of 724 psi.

This motor is now known to have been subjected to extremes of temperature or humidity while in the active force inventory. It was involved in a transportation accident and suffered damage to the forward skirt; however, this damage is not judged to be detrimental to the test objectives.

B. Test Loads and Arrangement

The pressurization system is in accordance with Drawing 12S00910, and is shown in Figure B-1. Three-charge-equipped burst discs are to be used for blowdown. The orifice size is to be 1.25 inches. The shaped charge on the pressurization burst disc is to be interrupted for 1 inch so that the disc center will be retained at the flange assembly. The accumulator pressure is to be 700 psi. The motor will be automatically vented when the pressure reached 640 psi by blowing three rupture discs.

The temperature of the motor and systems shall be $70^{\circ} \pm 2^{\circ}$ F. The motor shall be conditioned for a minimum of 108 hours before testing.

C. Data Requirements

Motor instrumentation locations are shown in Figures B-2 through B-4 and data acquisition requirements are given in Table B-1.

Deflectometers required at locations D1, D2, and D3 are to be installed using spacers between the instrument body and the grain to retract the pot as much as possible. Leadwires are to be brought out through the nozzle port or center port adjacent to the instrument location, except for Port 3. This is intended to minimize the movement of leadwires that occurred during the previous test.

Developed oscillograph traces, complete with calibration factors, shall be delivered to Product Engineering after the test. Digital plots at 4 ms shall be made of all data channels for the period of the pressure rise. Digital plots at 40 ms shall be made for the full test duration. All channels showing evidence of failure, to be selected by Product Engineering, shall be played from FM tapes onto oscillograph charts at a speed of 80 in./sec. Cross plots of selected channels may be requested by Product Engineering if considered necessary to define failure.

D. Photographic Coverage

Photographs will be taken of the interior of the motor after all instrumentation is installed. Still black and white photographs of the assembled test arrangement are required.

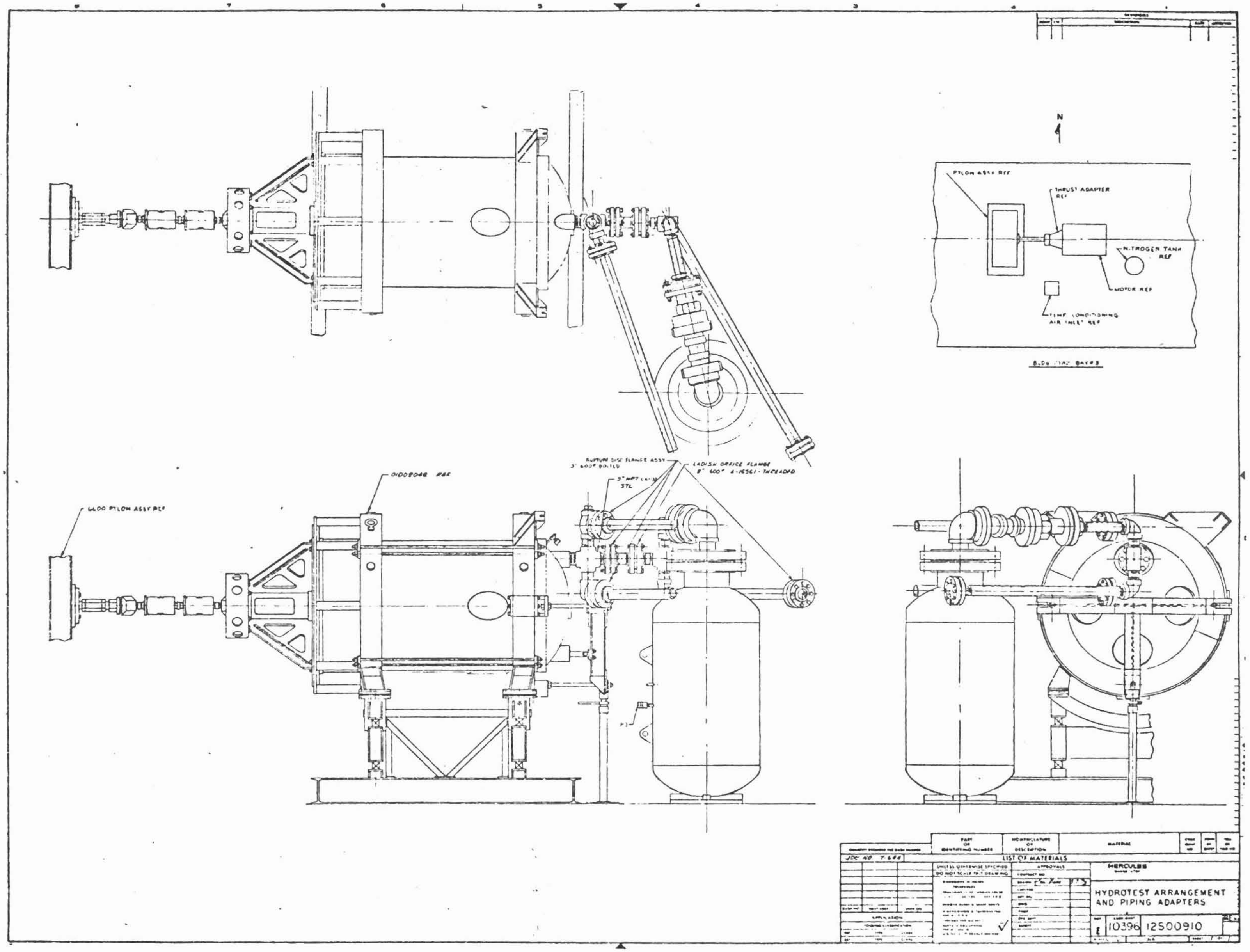


Figure B-1. Hydrotest Pressurization System

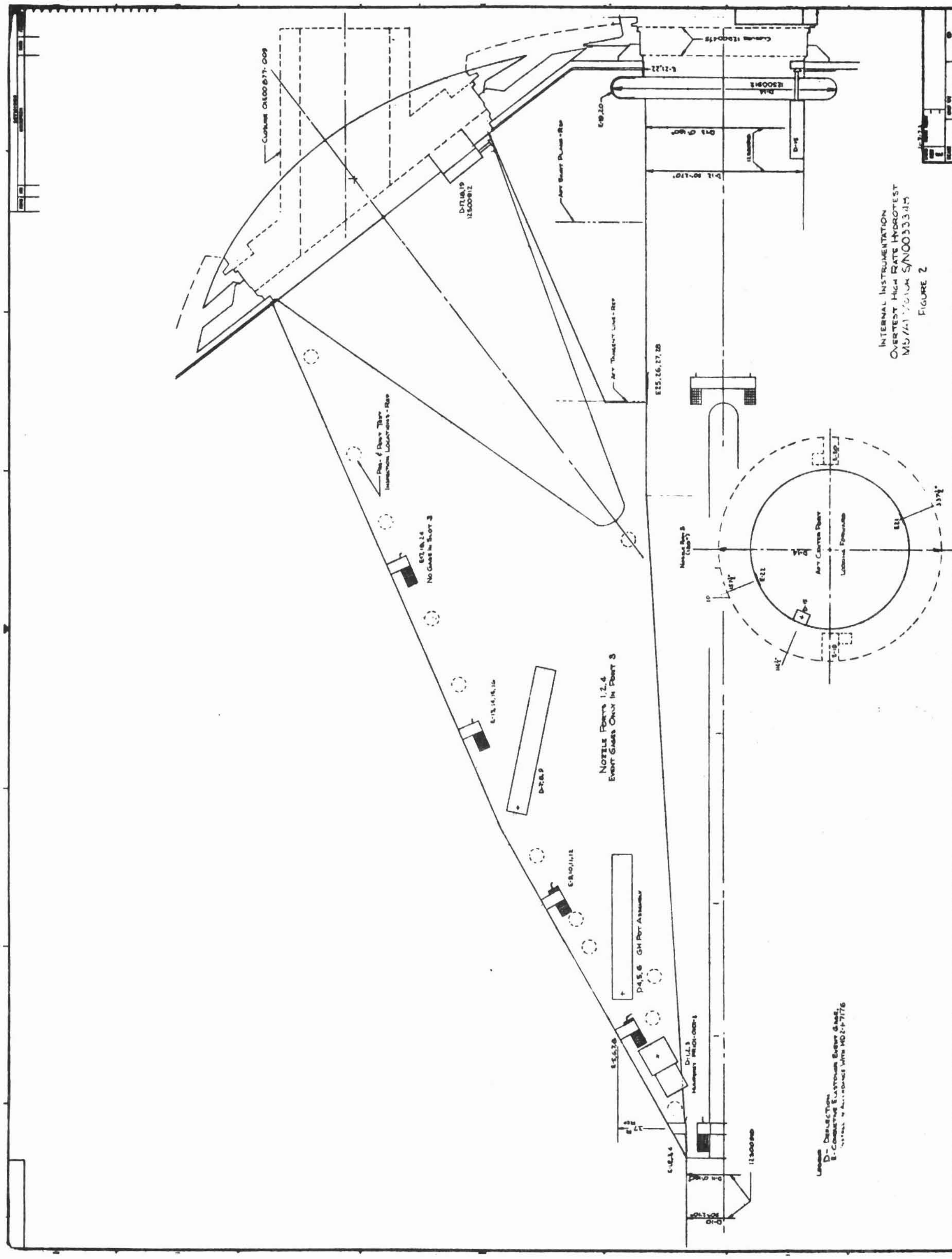


Figure B-2 Internal Instrumentation Overtest High Rate Hydroburst

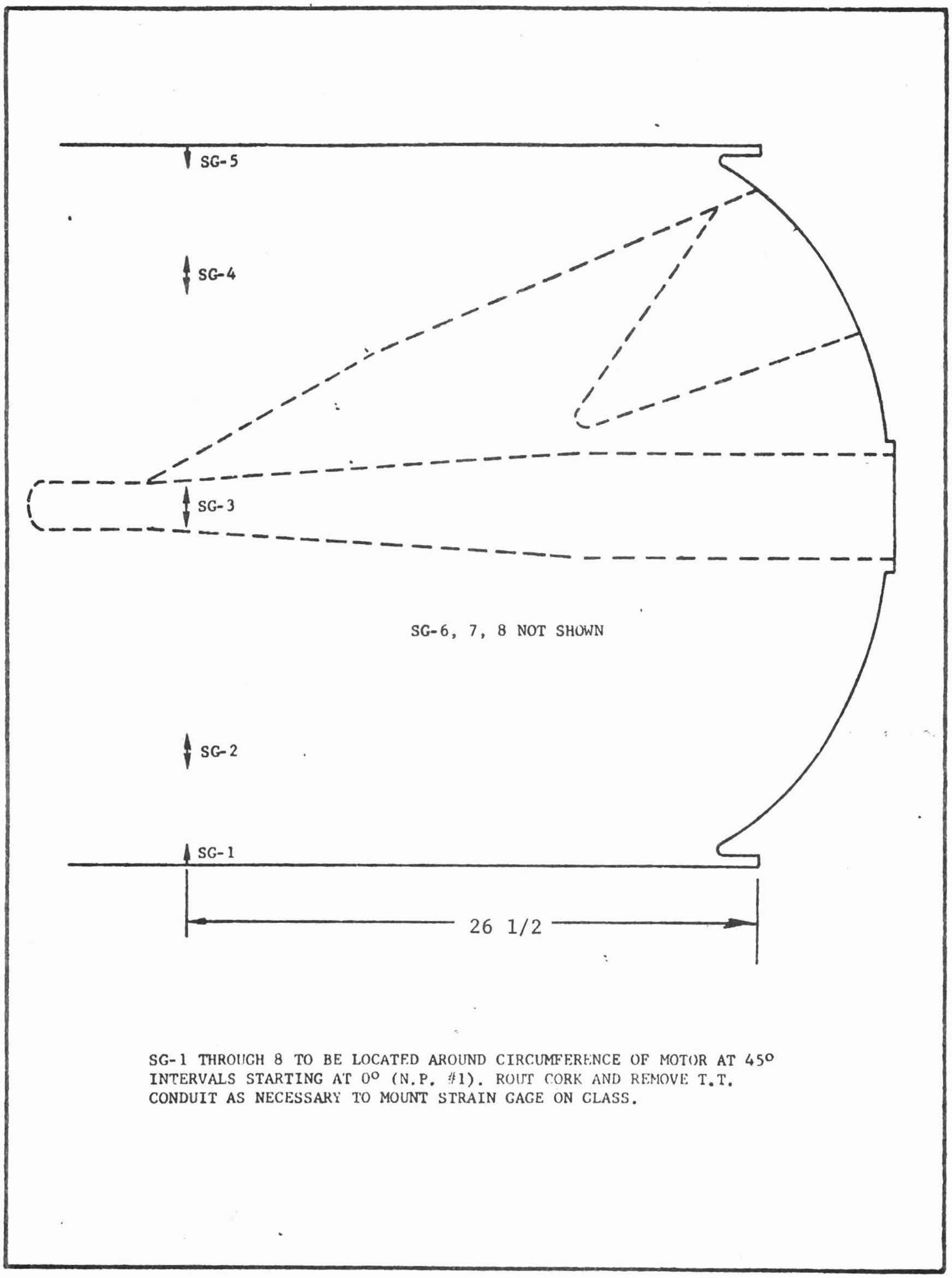


Figure B-3 External Strain Gage Location (Cylindrical Section)

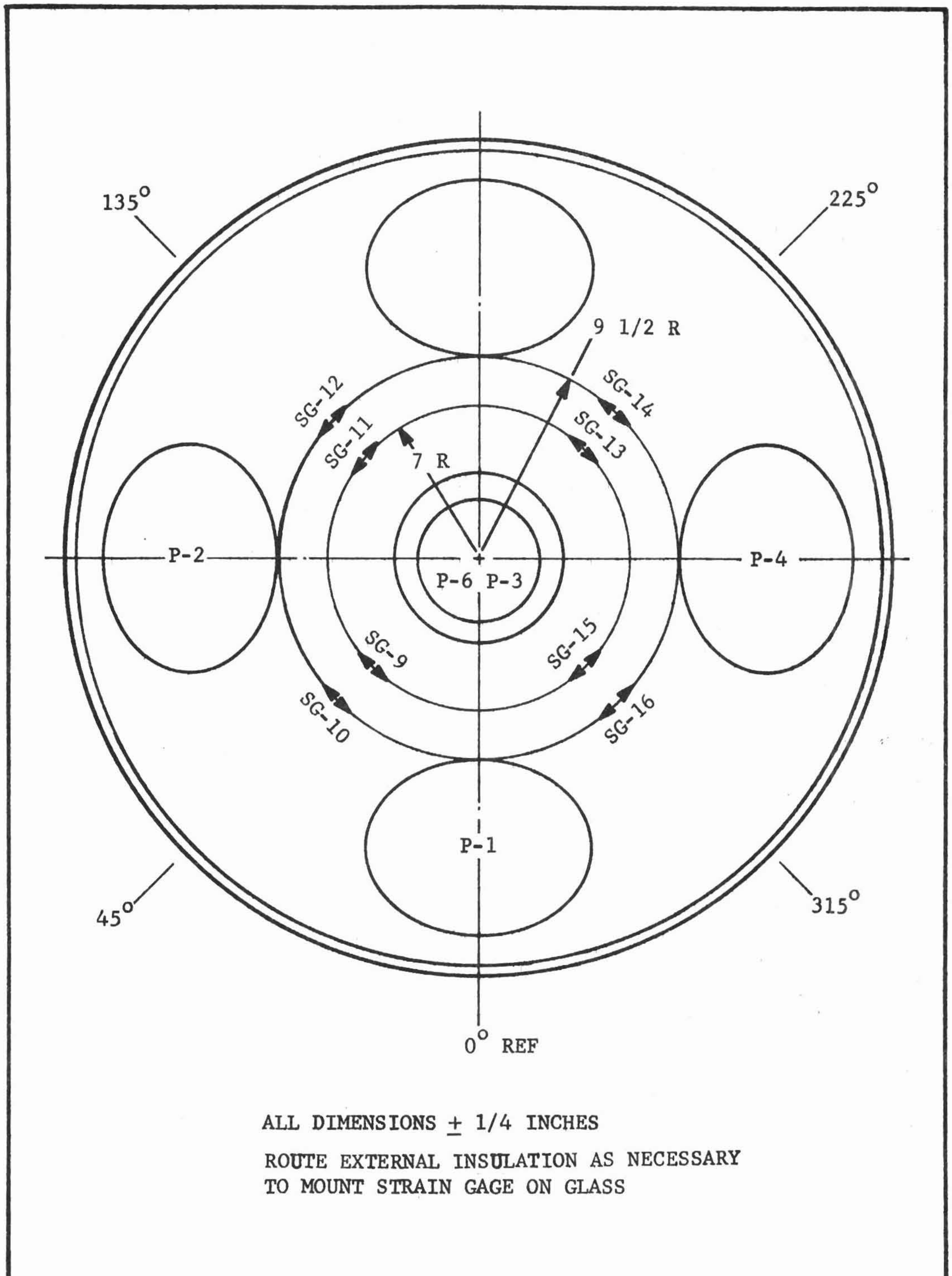


Figure B-4 External Instrumentation, Aft Dome

DATA ACQUISITION INSTRUCTIONS - TABLE B-1

BW-6000/435 (9-63)

CODES:

FM - Frequency Modulation (in./sec magnetic tape speed)
RO - Recording Oscillograph (in./sec)

I/C - Iron Constantan
C/A - Chromel/Alumel
P/P10%R - Platinum/Platinum 10% Rhodium
MV - Millivolts

MEASUREMENT PRIORITIES

1. Hold test until instrument is operative.
2. These measurements may be deleted only upon direction of the cognizant HPC test conductor.

TEST NO. S/N 0033348

SHEET 1 OF 2

MOTOR INSTRUMENT LIST S N M 1- 01AE003

APPROVED BY

MEASUREMENT NUMBER	TYPE: MEASUREMENT	TYPE: TRANSDUCER	LOCATION AND/OR INSTALLATION DRAWING	PRIORITY	PURPOSE OF MEASUREMENT	EXPECTED RANGE	RECORDING MODES
P1 P2 P4	Pressure	Pressure Transducer 0-1000 psi	See Figure 4	1	Monitor Motor Pressure at Nozzle Ports	0-700 psi	D-250 FM-60 RO-40
P3	Pressure	Pressure Transducer 0-1000 psi	See Figure 4	1	Monitor Motor Pressure at Aft Center Port	0-700 psi	D-250 FM-60 RO-40
P5	Pressure	Pressure Transducer 0-1000 psi	See Figure 1	1	Monitor Line Pressure	0-1000 psi	D-250 RO-40
E1 thru E18 E24*	Event	CON/RTV-1 Event Gage	See Figure 2	1	Monitor Wing Slot Cracking Event	0-10 MW	D-250 FM-60 RO-40 (E1 thru E12 Only)
E19 E20*	Event	CON/RTV-1 Event Gage	See Figure 2	2	Monitor Stress Relief Groove Cracking Event	0-10 MW	D-250 FM-60
E21 E22*	Event	CON/RTV-1 Event Gage	See Figure 2	2	Monitor Aft Center Port Boot-Flap Debonding	0-10 MW	D-250 FM-60
E25 thru E28*	Event	CON/RTV-1 Event Gage	See Figure 2	2	Monitor Aft Web Propellant Cracking	0-10 MW	D-250 FM-60 RO-40
D1 thru D3	Displace-ment	Deflec-tometer	See Figure 2 Humphrey RP 101-0101-1	1	Monitor Expansion of Wing Slot	0.6"	D-250 FM-60 RO-40
D4 thru D9	Displace-ment	Deflec-tometer	See Figure 2 Hummel Pot Assembly	1	Monitor Expansion of Wing Slot	0.8"	D-250 FM-60

DATA ACQUISITION INSTRUCTIONS - TABLE B-1 (Cont)

BW-6000 435 (9-63)

CODES:

FM - Frequency Modulation (in./sec magnetic tape speed)

RO - Recording Oscillograph (in./sec)

I/C - Iron Constantan

C/A - Chromel/Alumel

P/P10%R - Platinum/Platinum 10% Rhodium

MV - Millivolts

MEASUREMENT PRIORITIES

1. Hold test until instrument is operative.
2. These measurements may be deleted only upon direction of the cognizant HPC test conductor.

TEST NO. S/N 0033348

SHEET 2 OF 2

MOTOR INSTRUMENT LIST S N: M 1- 01AE003

APPROVED BY

MEASUREMENT NUMBER	TYPE: MEASUREMENT	TYPE: TRANSDUCER	LOCATION AND OR INSTALLATION DRAWING	PRIORITY	PURPOSE OF MEASUREMENT	EXPECTED RANGE	RECORDING MODES
D-10 D-11	Displace-ment	Linear Pot	See Figure 2 and 12S00911	2	Measure Expansion of Center Core Tip	0.6"	D-250 FM-60
D-12 D-13	Displace-ment	Deflec-tometer	See Figure 2 and 12S00911	2	Measure Expansion of Center Core	0.6"	D-250 FM-60
D-14	Displace-ment	Deflec-tometer	See Figure 2 and 12S00912	1	Measure Expansion of Stress Relief Groove	0.5"	D-250 FM-60
D-15	Displace-ment	Linear Pot	See Figure 2	2	Measure Axial Displace-ment of Aft Center Port	0.5"	D-250 FM-60
P-6**	Pressure	Kistler Transducer 0-1000 psi	See Figure 4	2	Monitor Motor Pressure at Center Port	0-700 psi	FM-60
P-7**	Pressure	Kistler Transducer 0-1000 psi	See Figure 4	2	Monitor Motor Pressure at Nozzle Port No. 2	0-700 psi	FM-60
D-17 thru D-19	Displace-ment	Linear Pot	See Figure 2 and 12S00912	2	Measure Radial Dis-placement of Nozzle Port	0.5"	D-250 DM-60 (D17 and 18 Only)
SG-1 thru SG-8	Strain	Strain Gage	See Figure 3	2	Monitor External Case Strain	1.5%	D-250 FM-60
SG-9 thru SG-16	Strain	Strain Gage	See Figure 4	2	Aft Dome Strain	1.5%	D-250 FM-60
Time Zero							All Systems
Dump Time Zero***							All Systems

Color movies shall be taken of the motor aft dome and unloading piston arrangement for full duration of the test (1 sec) at a film speed of 400 frames/sec. Film will not be developed unless a chamber failure occurs during test.

E. Test Changes

Any changes to the test plan will be documented on an Event Record (BW-6000/769) and approved by QA Test Engineering, Product Engineering, and Test Area Supervision.